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Metal-Oxide Surge Arresters in High-Voltage Power Systems

Fundamentals

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3rd edition

Answers for energy.

Foreword to the Third Edition

This handbook on surge arresters first appeared in 2001 as the first of two planned parts. It enjoyed considerable success and was translated into several languages. However, for personal and professional reasons it has not been possible to complete the second part until now. As a result, the handbook will not have two parts as originally conceived. To compensate, this edition includes some additional details that were deliberately omitted in the first two editions in order to preserve their status as fundamental works.

A number of developments have of course taken place since 2001 relating to the technology of surge arresters as well as standardization, necessitating a full revision. This means that this volume is once again a handbook on the fundamentals of metal-oxide surge arresters in high-voltage systems, reflecting the state-of-art in terms of technology and standards. It should enable a reader who is tackling this subject area for the first time to identify and to understand the main factors involved in sizing and selecting surge arresters, initially without the need to consult additional literature. To help with more difficult questions, a list of recent literature on surge arresters has been added to this volume.

The concept of the first edition has stood the test of time, and has been kept unchanged. First, the handbook contains some basic information about the use of surge arresters and how they work. Next, there is a description of the constructive design features of what is by far the most frequently used type – surge arresters for outdoor applications in high-voltage and medium-voltage systems. There follows a section detailing the systematic procedure for the electrical and mechanical design of a surge arrester. Actual design examples are then described. Finally, there is a section on the current standards applicable to surge arresters and their use, and a reference section containing definitions of terms.

Please note that the standards relating to surge arresters are again undergoing radical change. The next edition (Edition 3.0) of the surge arrester testing standard IEC 60099-4 will contain important changes to the definitions and test requirements of the energy handling capability. A similar development is taking place in the American surge arrester testing standard IEEE C62.11. As a result, it may be necessary to revise this handbook again in a few years. Until that time, we hope that it will be of use to all readers.

We would like to thank everyone who has contributed with valuable comments, criticisms and discussions during the production of this manual. As always, any comments or suggestions about how to improve the handbook will be gratefully received.

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Tasks and Operating Principles of Metal-Oxide Arresters

Surge arresters – or short, arresters – constitute an indispensable aid to [insulation coordination](#)¹ in electrical power supply systems. **Figure 1** makes this clear. There the voltages which may appear in a high-voltage electrical power system are given in per-unit of the peak value of the highest continuous phase-to-earth voltage², depending on the duration of their appearance.

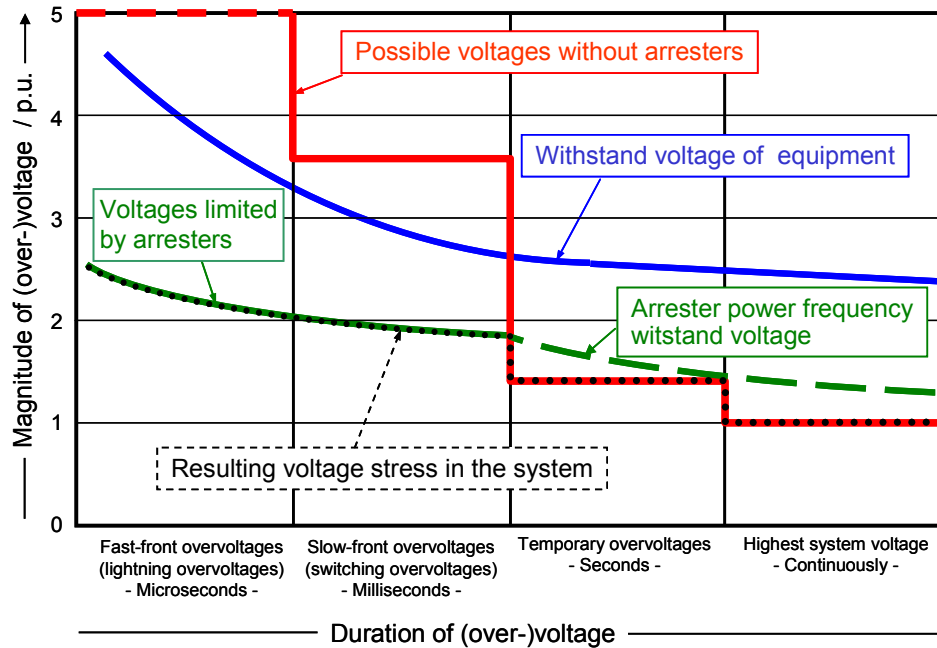


Fig. 1: Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system versus duration of their appearance (1 p.u. = $\sqrt{2} \cdot U_s / \sqrt{3}$)

The time axis is roughly divided into the range of fast-front overvoltages (mainly [lightning overvoltages](#)) in the microsecond range, slow-front overvoltages (mainly [switching overvoltages](#)) in the millisecond range³, [temporary overvoltages](#) in the second range – which are commonly cited by the abbreviation "TOV" – and finally the temporally unlimited highest continuous system operation voltage. The voltage or over-

¹ Underlined terms are explained in greater detail in the appendix. In the electronic version of the handbook, clicking on the terms will automatically call up the definitions.

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

³ To make the text easier to read, we will refer to "fast-front overvoltages" as lightning overvoltages, and "slow-front overvoltages" as switching overvoltages, even though the terms are not fully equivalent according to IEC 60071-1, Insulation Co-ordination.

voltage, which can be reached without the use of arresters, is a value of several p.u. If instead, one considers the curve of the [withstand voltage](#) of equipment insulation, (here equipment means electrical devices such as power transformers) one notices that starting in the range of switching overvoltages¹, and especially for lightning overvoltages, the equipment insulation cannot withstand the occurring dielectric stresses. At this point, the arresters intervene. While in operation, it is certain that the voltage that occurs at the terminal of the device – while maintaining an adequate safety margin – will stay below the withstand voltage. Arresters' effect, therefore, involves lightning and switching overvoltages². However, arresters cannot and are not expected to limit temporary overvoltages. They must instead be designed to withstand the continuous system operation voltage without sustaining damage. This is shown in Figure 1 by the dotted part of the arrester curve on the right, in which the arrester – like any other device in the system – must demonstrate sufficient operational stability over and above likely voltage stress.

Even though a great number of arresters which are [gapped arresters](#) with resistors made of [silicon-carbide](#) (SiC), are still in use, the arresters installed today are almost all [metal-oxide \(MO\) arresters](#) without gaps, which means arresters with resistors made of metal-oxide ([metal-oxide or MO resistors](#)). The distinctive feature of an MO resistor is its extremely non-linear [voltage-current or \$U\$ - \$I\$ -characteristic](#), rendering unnecessary the disconnection of the resistors from the line through serial spark-gaps, as is found in the arresters with SiC resistors. The currents passing through the arrester within the range of possibly applied power-frequency voltages are so small that the arrester almost behaves like an insulator. If, however, [surge currents](#) in the kiloampere range are injected into the arrester, such as is the case when lightning or switching overvoltages occur, then the resulting voltage across its terminals will remain low enough to protect the insulation of the associated device from the effects of overvoltage.

In **Figure 2**, an example is shown of the U - I -characteristic of a typical MO arrester connected between phase and ground in a solidly earthed neutral 420-kV-system³. On the ordinate the voltage peak value is depicted linearly, while on the abscissa current peak values are given in a logarithmic scale. In the depiction, the characteristic extends

¹ Switching overvoltages do not play an important role in the distribution and the lower-voltage transmission systems, but gain importance with increasing voltage level in the high- and extra-high-voltage systems.

⁴ It is extremely important when configuring arresters not to start with the [nominal system voltage \$U_n\$](#) (in this case, 380 kV), but instead with the [highest voltage of the system \$U_s\$](#) .

over a current range of 50 μA to 50 kA, that is, over nine decades of magnitude. Some important terms are explained below, moving from left to right on the characteristic.

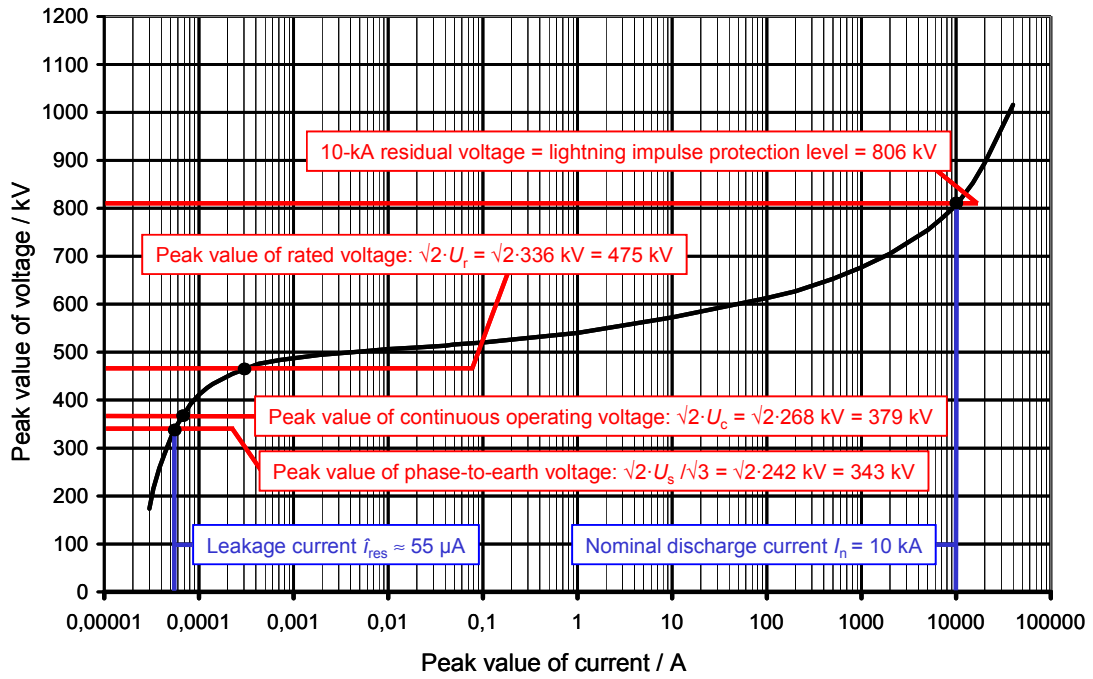


Fig. 2: U - I -characteristic of a typical MO arrester in a solidly earthed neutral 420-kV-system

The power-frequency voltage, while continuously applied to the arrester, is the highest phase-to-earth voltage of the system. In this case the peak value is:

$$\hat{u} = \sqrt{2} \cdot U_s / \sqrt{3} = \sqrt{2} \cdot 420 \text{ kV} / \sqrt{3} = 343 \text{ kV}$$

At the same time, the so-called [leakage current](#) flows through the arrester. This consists of a large capacitive and a considerably smaller, resistive component. All in all, the leakage current is – as can also be seen in **Figure 3** – for the most part capacitive. In the U - I -characteristic depiction, however, only the resistive component is represented. In this example it is $\hat{i}_{\text{res}} \approx 55 \mu\text{A}$, whereas the total current has a peak value of about 0.75 mA.

The next significant characteristic point is the [continuous operating voltage](#) of the arrester. For this, the formal symbol U_c is used in accordance with the [IEC](#) standards; in Anglo-American circles the term [MCOV](#) (Maximum Continuous Operating Voltage) is customary. This is the power-frequency voltage, which the arrester can be operated at, without any type of restrictions. All properties of the arrester, which have been demonstrated in the type tests, are valid, assuming that this arrester is energized at a voltage level equivalent to its continuous operating voltage. As is seen in Figure 2, the continuous operating voltage is greater than the highest continuously occurring phase-to-earth

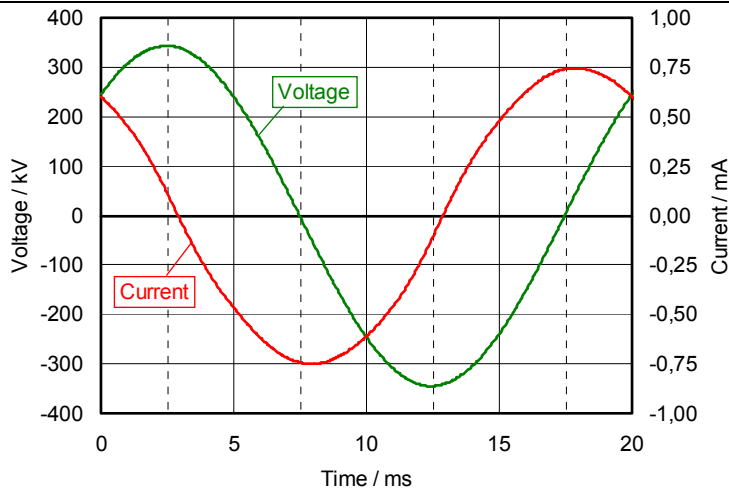


Fig. 3: Applied voltage and leakage current of the sample arrester of Fig. 2 when operated at phase-to-earth voltage ($U_s = 420$ kV, $U_r = 336$ kV)

voltage. An allowance of at least 5% (IEC 60099-5) is recommended. With this, possible harmonics in the system voltage are taken into account. In the chosen example the arrester shows a continuous operating voltage of $U_c = 268$ kV, which is almost 11% above the highest continuous possible phase-to-earth voltage¹.

The name of the next characteristic point is somewhat misleading. The [rated voltage](#) (the symbol: U_r) of a metal-oxide arrester is not, as one might at first assume, a voltage, which can be limitlessly applied (that one is the continuous operating voltage mentioned earlier). Instead it characterizes the capability of the arrester to deal with temporary overvoltages in the system. It can only be applied temporarily – the standards stipulate a time period of 10 seconds. Some manufacturers permit a time period of 100 seconds. The characteristic shows that under these conditions there is a leakage current (more precisely, its resistive component) of ca. 300 μ A. In extended operation, this would lead to an increased operating temperature of the arrester, but not within a time period of ten or even one hundred seconds. The actual cause of the temporary time limit is the sudden great increase in the temperature and the frequent rise in leakage current due to its positive temperature coefficient (the temperature-dependence of the U - I -characteristic is not shown in the simplified depiction in Figure 2), after, for example, the arrester has diverted a current impulse to the ground (that is, after it had to "operate"). In this case an extensive application of the rated voltage could render the arrester incapable of recooling; instead it would become [thermally unstable](#) and would continually heat up until it reached self-destruction (so-called [thermal runaway](#)).

¹ Choosing a higher continuous operating voltage than is minimally required has a beneficial effect on the stability of an arrester in continuous operation; see the section called "Configuring MO Arresters".

The rated and continuous operating voltage of an arrester are directly related to each other. The value of this ratio is almost always 1.25, with only a few exceptions, and is not manufacturer-dependent¹. As a result in the chosen example, the rated voltage is $U_r = 1.25 \cdot U_c \approx 336 \text{ kV}$ ².

This concludes the description of the part of the U - I -characteristic curve relevant to power-frequency voltage. The curve then continues into an area in which even minimal voltage increases lead to a significant rise in the current. It is reserved for transient events within a time range of milli- and microseconds, in other words, for switching and lightning overvoltages. The sustained application of power-frequency voltage in this area of the characteristic would destroy the arrester in a fraction of a second.

The characteristic in the region of currents greater than about 100 A describes the protective characteristic of the arrester. Its most important parameter is the [lightning impulse protective level](#) depicted in Figure 2. This depicts the voltage, which drops across the arrester terminals when the [nominal discharge current](#) flows through the arrester. The aforementioned is a [lightning current impulse](#) of a standardized shape, whose amplitude is assigned to different classes from 1.5 kA to 20 kA, according to the IEC standard 60099-4. For high-voltage arresters (in systems with $U_s \geq 72.5 \text{ kV}$) only classes 10 kA and 20 kA are common, and for medium-voltage arresters ($U_s \leq 52 \text{ kV}$) the value of 5 kA is very important. The nominal discharge current divulges little about the properties of the arrester. Two "10-kA-arresters" can have very different properties. When selecting an arrester the nominal discharge current therefore cannot be considered on its own. For the example in Figure 2, a 10-kA-arrester was selected. The statement "lightning impulse protective level = 806 kV" means the following: a voltage at a maximum of 806 kV drops across the terminals when impressing a lightning current impulse of 8 μs of [virtual front time](#), 20 μs of [virtual time to half-value on the tail](#) and a peak value of 10 kA. These relationships are likewise depicted in **Figure 4**.

¹ Nevertheless there is no direct physical explanation for this relationship. It was found to be purely empirical.

² When rounding off in these calculations, deviations of up to 1 kV can occur. See the layout examples at the end of the handbook.

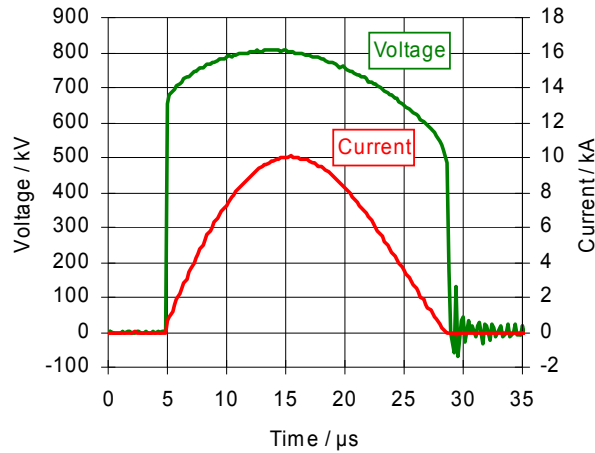


Fig. 4: Residual voltage of the sample arrester of Fig. 2 ($U_r = 336$ kV) at nominal discharge current ($I_n = 10$ kA)

A lightning impulse protective level of 806 kV means that the peak value of the terminal voltage during a discharge, starting from normal operation at phase-to-earth voltage, increases by a factor of about 2.35 (806 kV compared to 343 kV), while at the same time the current amplitude increases by at least eight decades of magnitude (from 55 μ A to 10 kA). This substantiates the extreme non-linearity of the arrester's voltage-current-characteristic.

Equipment in the 420-kV-system normally has a [standard lightning impulse withstand voltage](#)¹ (LIWV) of 1425 kV. This (test voltage) value, however, is not allowed to ever be attained in practice. In accordance with the application guide on insulation coordination, IEC 60071-2, the highest occurring voltage in the case of a non-self-restoring insulation in operation should stay below this value by a factor of 1.15, that is, not exceed 1239 kV. Nevertheless, the lightning impulse protective level of 806 kV of the sample arrester seems at first to offer more than enough protection. It should, however, be noted that this value represents a *voltage across the arrester terminals*, caused by the flow of an ideal standardized test current at the same level as the arrester's nominal discharge current. Three significant causes can allow the voltage at *the terminals of the equipment to be protected* to take on a considerably higher value:

¹ Frequently BIL – basic lightning impulse insulation level – is mentioned in this context. This term from the US standards is, however, not defined in the IEC standards (see the comment on [BIL](#) in the appendix). According to the IEC, the correct term is "standard rated lightning impulse voltage", which is abbreviated to LIWV.

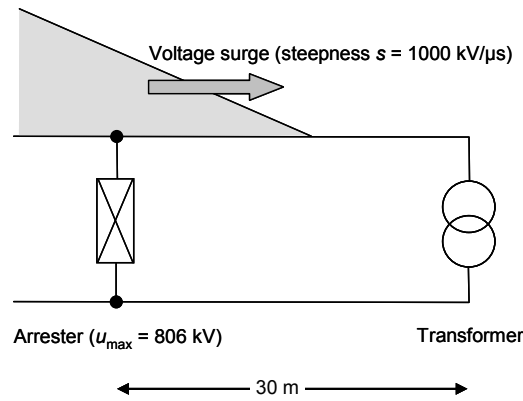


Fig. 5: Simplified arrangement to illustrate the protective zone of an arrester (explanation see text)

- a) **Traveling wave processes:** Rapidly increasing overvoltages spread in the form of [traveling waves](#) on the line. In those places where the [surge impedance](#) of the line changes, refraction and reflection occur. Especially, a voltage wave will be totally positively reflected when reaching an unterminated end of the line. The voltage level at every instant and at every point on the line results from the sum of the different instantaneous values of each individual voltage wave. Thus, at the terminated end this value will be doubled. A connected transformer appears similar to an unterminated end since its winding inductivity for rapid functions exhibits a great impedance compared with the surge impedance of the line. The consequences of this are explained by means of a simplified example (**Figure 5**). An overvoltage surge with a front steepness of $1000 \text{ kV}/\mu\text{s}$ runs towards a transformer. The propagation rate of such a surge on an overhead line, as in this example, is the speed of light, that is at $300,000 \text{ km/s}$ or $300 \text{ m}/\mu\text{s}$. It is assumed that this arrester is an ideal one, which behaves like an insulator up to a voltage level of 806 kV , while higher overvoltages are limited to exactly 806 kV . The overvoltage surge first passes by the arrester and reaches the transformer $0.1 \mu\text{s}$ later, which is the propagation time on the 30 m long stretch between the arrester and the transformer. At this time the voltage at the arrester has reached a value of $1000 \text{ kV}/\mu\text{s} \cdot 0.1 \mu\text{s} = 100 \text{ kV}$. Thus, the arrester is still behaving like an insulator. At the transformer the arriving surge is reflected. That is why an additional voltage surge, with the same shape and polarity, runs back from there. The superimposition of both surges causes the voltage at the transformer to increase at double the steepness, thus at $2000 \text{ kV}/\mu\text{s}$. Another $0.1 \mu\text{s}$ means a voltage there of 200 kV . At the same time the reflected surge has reached the arrester, whose voltage up to this point in time has increased at the original rate of rise and, therefore, in the meantime, has also reached a voltage level of 200 kV . From now on the original and the reflected surges are superimposed on the arrester, and the voltage increases at a steepness of $2000 \text{ kV}/\mu\text{s}$ not only at the transformer, but also here. The situation at

the arrester does not change until the voltage at its terminals has reached the limiting value of 806 kV. In accordance with the starting assumption, a higher value cannot be taken on. According to the rules of traveling wave processes, this can only be reached if, from now on, a negative voltage surge with a steepness of 2000 kV/μs spreads out to both sides from the arrester. The superimposition of the original surge on that which was reflected from the transformer, and which is now again reflected from the arrester, causes the voltage at the arrester to maintain a constant value of 806 kV. Another 0.1 μs passes – the propagation time needed for the 30 m stretch between the arrester and the transformer – before the negative surge reflected from the arrester reaches the transformer. During this time, however, the voltage there has already increased by 200 kV. Therefore, it already has a value of 1006 kV. Only now the arrester makes itself "noticeable" at the transformer and reduces the attained voltage¹. The example shows that the voltage at the equipment to be protected can be considerably higher than that found at the arrester. Exactly how high depends mostly upon the distance between the arrester and the device to be protected, and on the front steepness of the voltage surge (the same example with double the distance and an only 10% greater rate of increase for the voltage would cause the given maximum permissible voltage of 1239 kV to already be exceeded at the transformer)². This example makes it clear that the arrester has only a limited local [protective zone](#)!

- b) **Inductive voltage drops:** The current path shown in **Figure 6** of the discharge current from the termination of the arrester to the overhead line conductor, down to the effective earth, is ten meters long. At a specific value of 1 μH per meter (guide value for the typical inductance of a stretched conductor at a great distance from other live or earthed parts) its inductivity is 10 μH. A steepness of 10 kA/μs of a lightning current impulse can typically be expected. Under these conditions the inductive voltage drop of the shown arrangement is

$$u = L \cdot \frac{di}{dt} = 10 \mu\text{H} \cdot 10 \text{ kA}/\mu\text{s} = 100 \text{ kV}$$

¹ Since the arriving negative surge is reflected again in its full magnitude, not only does the voltage limit of 1006 kV result after the superimposition of all the partial surges at the transformer, but also a voltage reduction. If one carries out the calculation in the manner described, the transformer takes on an oscillating voltage with a maximum value of 1006 kV. In practice, the amplitude and shape of the oscillation are damped by various influences not considered here.

² You are reminded that the *amplitude* of the original voltage surge has no effect on the described procedure provided it is above the protective level of the arrester.

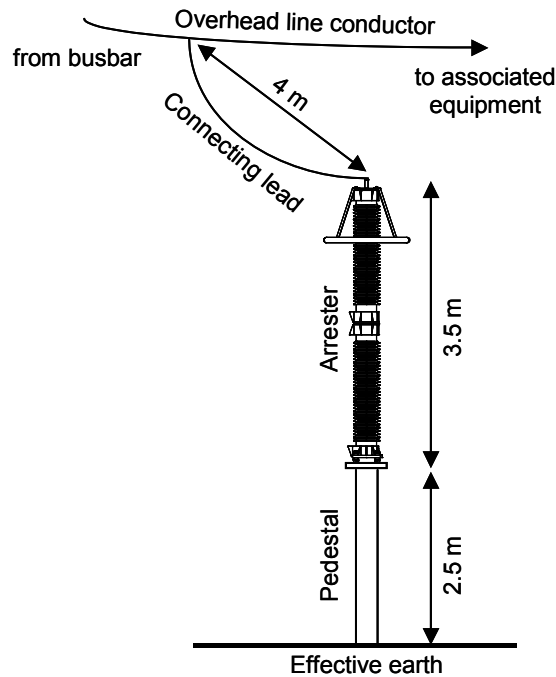


Fig. 6: Typical arrangement of an arrester in a 420-kV substation

This does not necessarily appear exactly simultaneously at the peak value of the arrester residual voltage. However, this value of 100 kV demonstrates the order of magnitude of possible inductive voltage drops which can superimpose the arrester residual voltage.

- c) **Discharge currents higher than the arrester nominal discharge current:** the protective level of the arrester is defined as its residual voltage at the nominal discharge current. Higher discharge currents may also occur. The arrester can withstand this undamaged, but it results in a higher residual voltage across its terminals depending on the shape of the U - I -characteristic (5% to 15% increase for double the current amplitude).

Thus, when choosing an arrester protective level, certain details must be considered, such as the distance between the arrester and the device to be protected, the particular substation configuration or the typical overvoltage stress in the system. If the distances are not chosen too large, a factor of at least 1.4 between the standard lightning impulse withstand voltage of the device to be protected and the lightning impulse protective level of the arrester normally leads to safe protection against fast-front overvoltages. In problematic cases, however, for example when [very-fast-front overvoltages](#) are to be expected, or when there are unusually great distances between the arrester and the de-

vice to be protected, the protective effect must be individually checked by means of a detailed calculation.¹

Not only is configuring for stable continuous operation (U - I -characteristic in the leakage current range) and choosing sufficiently low protective levels (U - I -characteristic curve in the high current range) necessary, but the arrester must also possess the necessary [energy handling capability](#) for each individual application. In the process, two different aspects must be considered:

The energy, which is instantaneously injected during a single discharge, is not allowed to exceed a value at which the metal-oxide resistors will be thermo-mechanically overstressed. Thus, one speaks in this context of the [single impulse energy handling capability](#) of an arrester. Energy that is injected within only a few micro- or milliseconds causes extreme, sudden temperature rises associated with excessive tensile and compressive forces acting on the MO resistor ceramic. This can lead to fine cracks or even cause the resistors to break. The effect is supported by the smallest inhomogeneities in the ceramic of the MO resistors, which despite the highly developed manufacturing technology are basically unavoidable. They may cause locally limited overheating of the ceramic in case of extremely high current and energy densities, respectively. Since the heat cannot spread fast enough into the surrounding material, additional thermo-mechanical stresses occur. By similar means hot channels may develop at locations of inhomogeneities, leading to electrical puncturing of the resistor. In addition, an external flashover may occur. The single impulse energy handling capability is thus largely a characteristic property of the metal-oxide resistor inserted in the arrester, practically independent of the rest of the arrester design. It is specified by the manufacturer with a sufficient safety margin to the actual limits.

Totally different contexts are valid for the [thermal energy handling capability](#). This is defined as the maximum level of energy injected into the arrester, at which it can still cool back down to its normal operating temperature. **Figure 7** illustrates this problem: the electric power loss resulting from the continuously applied power-frequency voltage is temperature-dependent. It rises overproportionally as the temperature increases. On the other hand, because of its design, the arrester can only dissipate a certain limited amount of heat into the surroundings. Indeed, this heat dissipation value also rises with the temperature, however, not nearly as much as the electric power loss does. Both

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

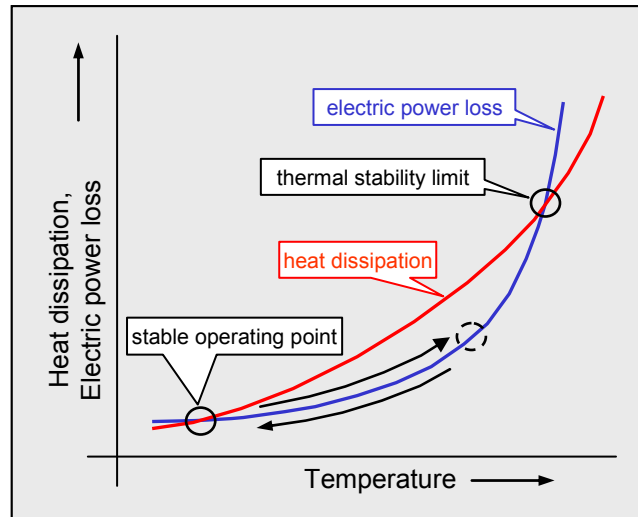


Fig. 7: Explanation of the thermal stability

power curves have two common points of intersection. The left one is a stable operating point. At this point exactly as much heat is dissipated to the outside, as is produced in the MO resistor: a thermal balance prevails. A discharge operation disturbs this balance. The energy, which is introduced, increases the temperature rapidly, and the operating point moves to the right on the power loss curve, as is shown with an arrow in Figure 7. As long as the right point of intersection of the curves is not reached, the heat generated by electric power loss can easily be dissipated, and the arrester can return to the stable operating point. If, however, the right point of intersection is reached or exceeded, then cooling is no longer possible. The arrester then becomes thermally unstable and heats up until it self-destroys. This point of intersection, therefore, represents the [thermal stability limit](#). The thermal energy handling capability is specified in such a way that the related temperature increase brings the arrester to a temperature which exhibits an adequate safety margin to the thermal stability limit. The actual thermal stability limit depends on the overall arrester design and has a value of typically between 190 °C and 220 °C.

Both definitions of the energy handling capability cited above are not specified in the same way in the standards. According to the decisive IEC standard 60099-4 on metal-oxide surge arresters without gaps, the energy handling capability is only described by means of, what is known as, the [line discharge class](#). Its definition is, however, compli-

cated. Indirectly it is about the thermal energy handling capability. This will be dealt with more thoroughly later in this chapter.¹

With respect to the energy handling capability, it must finally be mentioned that arresters normally are designed to divert to the ground only a fraction of the charge that is introduced to the overhead line conductor as a result of a direct lightning strike. In this case, it is assumed that the overvoltage, which occurs on the overhead line conductor, will cause a flashover of one or more line insulators. The greatest part of the charge is thus diverted through the flashover channels towards the ground. Only overvoltages limited to the insulator flashover voltage and the related currents associated over the surge impedance of the line, with the appropriately reduced charge content, will finally reach the stations (switchyards, transformer substations), and only these must further be limited by the arresters in the station or their contained charge further diverted to the ground.

In medium-voltage distribution systems the arresters are widely spread over the whole network as they are normally directly arranged either, for instance, at the pole-mounted transformers, or at the cable terminations. Once in a while, lightning may hit the line so closely to the arrester, that it is only relieved a little or not at all by insulators flashing over. This is known as a [nearby direct lightning strike](#) and a common cause for arrester failures in these systems. Attempts to avoid this in high-voltage transmission systems are made by improving the shielding of the line, for example, by installing a second overhead shield wire next to the station. That is why nearby direct lightning strikes almost never occur in conjunction with high-voltage station arresters. As a result their failure rate is about one order of magnitude lower than that of distribution arresters.

¹ The system of line discharge classes is currently under discussion. The next edition of IEC 60099-4 is likely to abandon this system and replace it with purely charge-based and energy-based definitions, systematically differentiated on the basis of thermal and impulse stress.

Constructive Design of MO Arresters

This chapter describes the basic constructive design of MO arresters. From the many possible ways to construct an arrester, only a few examples have been chosen so that the principle is clear.

The fact that there is no longer any need for serial gaps, which were mandatory for the gapped SiC arresters, has simplified the design of arresters considerably. Certain designs of the polymer-housed arresters were in fact impossible to construct until the gapless metal-oxide technique was introduced. As a major progress, MO arresters could be built with only one single effective active element, namely the column of the MO resistors. High demands are, however, made on these MO resistors, as they combine all the functions, which previously had been shared among the different components of the gapped arrester. In this way they have to be ageing resistant while being subjected to the constantly applied operating voltage. They must be able to absorb the energy injected and to divert the charge, respectively, during a discharge, and they should subsequently limit the follow current (leakage current) to values small enough for thermally stable operation. As a result, development of the MO resistors and their manufacturing technology – the production of MO resistors is considerably more complicated than that of SiC resistors – are of particularly great importance. This is not discussed any further here. Only the constructive design of an MO arrester will be dealt with here.

Figure 8 shows the cross section of a [unit](#) of an MO arrester with porcelain housing to be applied in a high-voltage system. The **MO resistor column**, together with the accompanying supporting construction, comprises the actual [active part](#) of the arrester. The column consists of individual MO resistors stacked on top of each other. The MO resistors are almost always produced in a cylindrical form (**Figure 9**)¹. Their diameter decisively determines the energy handling, the current carrying capability and the protective level. It is within a range of about 30 mm when used for distribution systems, and up to 100 mm or more for high- and extra-high-voltage systems and special applications, for which high energy handling capabilities are required². For especially high

¹ Some manufacturers, especially Japanese ones, also use designs with center holes, forms which are similar to toroids ("donuts"). For low voltage varistors square designs are also common.

² Actually the volume of the MO resistors is the decisive value. But for any given protective level of an arrester the length of the MO resistor column is more or less fixed, so that the energy handling capability can only be affected by the diameter of the MO resistors.

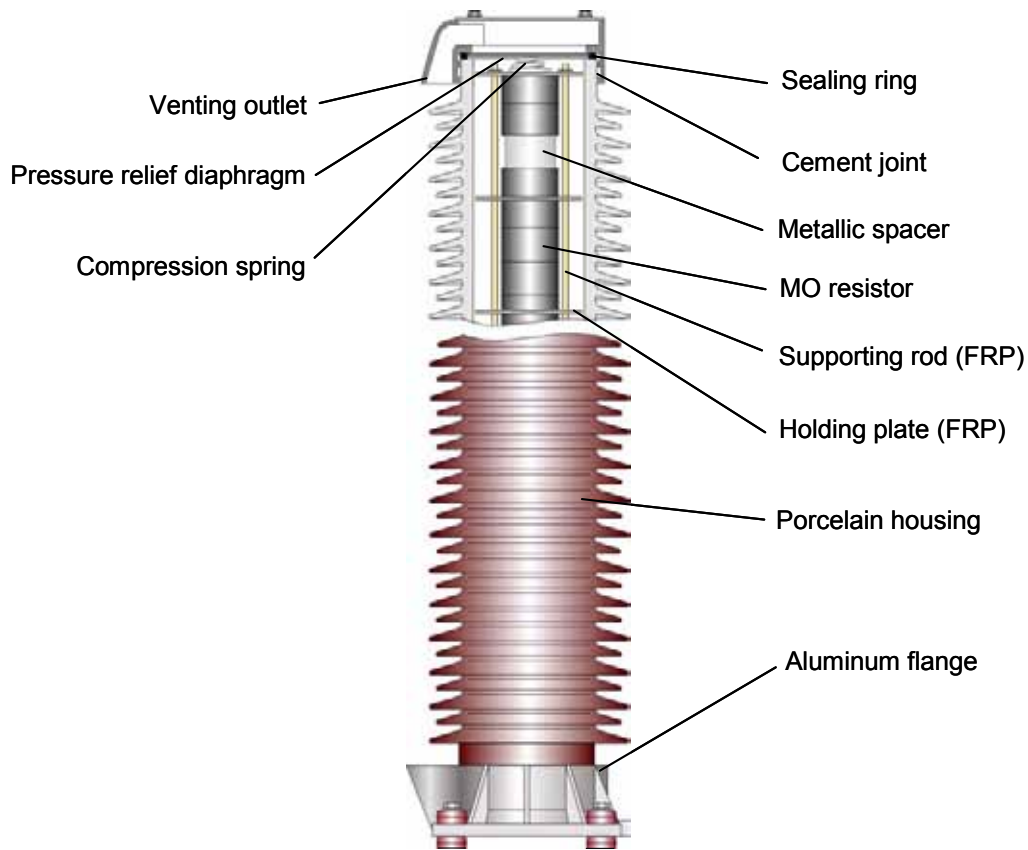


Fig. 8: Cross-sectional drawing of the unit of a porcelain housed MO arrester

demands, active parts are also realized in a multi-column technique, that is, two or more columns are connected in parallel.

MO resistors vary in height between ca. 20 mm and 45 mm. For the most part, the height is associated with the production and depends on the available tools and manufacturing facilities. However, not every height can be manufactured, since the greater the height (as well as the diameter), the harder it is to achieve sufficient homogeneity of the resistor material during manufacturing. This, however, decides most of all upon the energy handling capability and even more upon the reproducibility of specified technical data.

The U - I -characteristic of an MO resistor or a complete MO arrester is based on the field strength-current density characteristic (E - J -characteristic) of the underlying material system, which is dependent upon the substances contained and the production technology. It is easily calculated by multiplying the field strength with the relevant height and the current density with the relevant cross-sectional area.



Fig. 9: Metal-oxide resistors

The residual voltage per millimeter of height during a lightning current impulse of 10 kA peak value – the specific 10 kA residual voltage – is within a range of about 450 V/mm for a typical MO resistor in a distribution arrester (32 mm diameter) down to about 330 V/mm for a 100 mm diameter resistor used in extra high-voltage systems.¹ Typically, 60 mm diameter MO resistors would be used for an arrester in the 420-kV-system. With a standard height of 36 mm and a specific 10 kA residual voltage of 360 V/mm, each individual resistor has a 10 kA residual voltage of about 13 kV. In order to achieve a lightning impulse protective level of 806 kV, as in the example in Figure 2, 62 resistors would have to be stacked on top of each other. The resulting height of the MO resistor column of more than 2.2 meters could indeed be contained in a single porcelain housing. However, for dielectric reasons (clearance and creepage distance requirements) the housing must be designed to be considerably longer, so that arresters in the 420 kV network typically consist of at least two units in series. This example shows that the height of the arrester is, in most cases, not determined by the height of the active part.

The length of the active part is fitted to the housing length of the unit by means of **metallic spacers**. In the simplest cases these are aluminum tubes with end covers in order to achieve an evenly distributed contact pressure. Sometimes, however, massive aluminum parts are inserted, which at the same time serve as heat sinks, thereby increasing the thermal energy handling capability of the arresters.

The MO resistors stacked on top of each other in this way have to be mechanically fixed in the housing. The aim is, on the one hand, to ensure that the active part cannot

¹ The main reasons for these differences are the different current densities, depending on which diameters are used, based on a current value of 10 kA. The lower the current density, the lower the residual voltage.

be moved out of its original position during transportation¹, or when the arrester is installed in a position which is other than vertical. On the other hand, a certain axial contact pressure is necessary, so that the occurring current stresses can be easily handled. Figure 8 depicts one of the many achievable possibilities. Several **supporting rods** out of [FRP \(fiber-glass reinforced plastic\)](#) material encircle the MO resistor column like a cage. **Holding plates** – also out of FRP – additionally provided at regular intervals, on the one hand, prevent the supporting rods from being bent apart, and on the other hand, limit possible sagging of the whole construction towards the housing walls. A strong **compression spring** (for higher requirements, possibly more than one) which is attached to the upper end of the column braces the active part in the housing.

High demands are made on the electrical and mechanical properties of the whole supporting construction. It must be designed and implemented in such a way that it remains free of electric partial discharges under all operating conditions. In addition to high mechanical strength, high temperature resistance and high tracking and erosion resistance, as well as flame retardant and self-extinguishing properties in case of fire are required.

Until well into the 1980s in all cases, and for most high-voltage applications still today – as shown in Figure 8 – **porcelain** was used for the arrester housing. The ends of the housing are equipped with **aluminum flanges**², which are applied with the help of **cement**³. When choosing aluminum material of a quality for outdoor use, external paint is not necessary for the flanges.

[Sulfur cement](#) is the first choice for cementing. Besides favorable mechanical properties, it also proves to have advantages over [Portland cement](#), which is quite common in the insulator industry, in the manufacturing process: it can easily be brought into contact with aluminum without causing corrosion, and it can be quickly processed, since directly after application it already almost reaches its mechanical final strength.

Assuming the flanges and the end sections of the porcelain housing are appropriately designed, it is possible to achieve a cement joint that is always mechanically stronger

¹ Transport is often responsible for the highest mechanical stress to which an arrester is subjected in its entire service life.

² Sometimes when mechanical requirements are particularly high, steel flanges are also used.

³ Designs with clamped-on flanges are also common.

than the porcelain itself. That means that the strength of the porcelain can fully be made use of, when specifying the permissible mechanical head loads of the arrester housing.

Insulator porcelain is manufactured in different qualities, for which the minimum requirements are found in standards, e.g., IEC 60672-3. For arrester housings normally two qualities are used: the [quartz porcelain](#) (subgroup "C 110: siliceous porcelains" according to IEC 60672-3) and the [alumina porcelain](#) (subgroup "C 120: aluminous porcelains"). Higher mechanical strength can be achieved with alumina porcelain which, in comparison to the quartz porcelain, has about double the amount of specific strength. One important influence on the mechanical strength is the glaze, which is applied not only to the outside, but also to the inside of the porcelain walls. The strength of the housing naturally depends greatly on the geometry of the porcelain as well. Not only the wall thickness, but also the diameter play an important role here. The higher the system voltage, and as a result the greater the requirements on mechanical strength, the greater the diameter of the porcelain that will be chosen¹.

The color of the glaze, however, has no technical significance. The most common color is brown (color RAL 8016). Frequently, however, especially in the Anglo-American regions, a light gray tone is preferred. A certain influence of the color on the inner-arrester temperature, because of different thermal emittance and absorption coefficients, can be theoretically derived. Its total effect, however, remains negligible, such that for practical purposes, it is not taken into consideration.

Besides protecting the active part from environmental influences, the arrester housing above should also provide an adequate creepage distance. For this reason it is equipped with sheds whose designs can differ greatly. For the design of the shed profile (distances, overhang, angle of inclination) the application guide series IEC 60815 makes recommendations which should be followed by the manufacturer. The most noticeable is the difference between an alternating and a normal shed profile (**Figure 10**). No general recommendation can be made about which of the two types is more preferable. The advantages of the alternating shed profile include the prevention of continuous conductive layers from appearing on the surface, and that a large ratio of the creepage distance

¹ A bigger porcelain diameter can also be appropriate for reasons of short-circuit withstand capability and of the operational performance under polluted conditions. In brief: bigger diameters cause, on the one hand, stronger electric discharge activities on the surface, which, on the other hand, have less thermal impact on the arrester's active part due to the large distance and consequently small coupling capacitances between the outer surface and the MO resistors. Also internal radial electric field stress and thus the risk of inner partial discharges is much lower for bigger housing diameters.

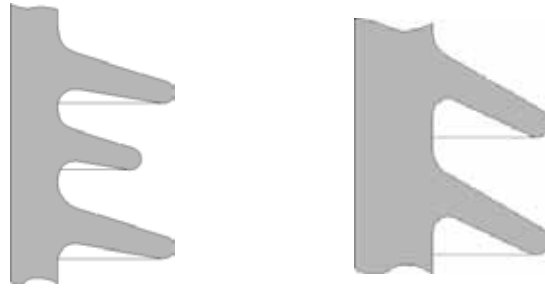


Fig. 10: Alternating shed profile (left) and normal shed profile (right)

to the total length can be achieved, which at any creepage distance requirements leads to shorter arrester housings. In artificial pollution tests in salt fog (in accordance with the standard IEC 60507), it generally performs better than the comparable normal shed profile. The latter, on the other hand, proves to have particularly good self-cleaning properties under real service conditions, and as a result, in many cases it has an excellent service record. In case of doubt when choosing a shed profile, the user's individual operational experience at a specific site should be considered.

The commentary to Figure 8 concludes with a description of the sealing system. This is one of the most critical components of the arrester; the type of failure in arresters most frequently mentioned in arrester literature and by users is leakage. The sealing system has three tasks to fulfill, which are quite incompatible with each other. On the one hand, it must deter the ingress of moisture for the duration of the lifetime of the arrester – the duration is meant to be 25 to 30 years. On the other hand, it should act as a fast operating pressure relief device in the rare event of an arrester overload, which can cause a rapid build-up of pressure in the housing, and would otherwise lead to a violent shattering of the porcelain body. Finally, at this point, a well-defined electric current transfer from the flange to the MO resistor column must be established.

The example shown in **Figure 11** consists of a sealing system, which for the most part is made up of a **sealing ring** and a **pressure relief diaphragm**. Both elements appear twice, that is at each end of the housing. The sealing ring is attached to the end face of the porcelain body. When the sealing occurs at this point then the cement between the flange and the porcelain is not part of the sealing system. This reduces the requirements on the cement bonding, but requires absolute care when working the porcelain end faces and during the subsequent quality control.

Great demands are made most of all on the material of the sealing ring. Thus, for example, natural rubber proved to be unsuitable, since with time it becomes brittle. Re-

sistance to ozone is another elementary requirement, which nowadays can be fulfilled with the use of synthetic materials.

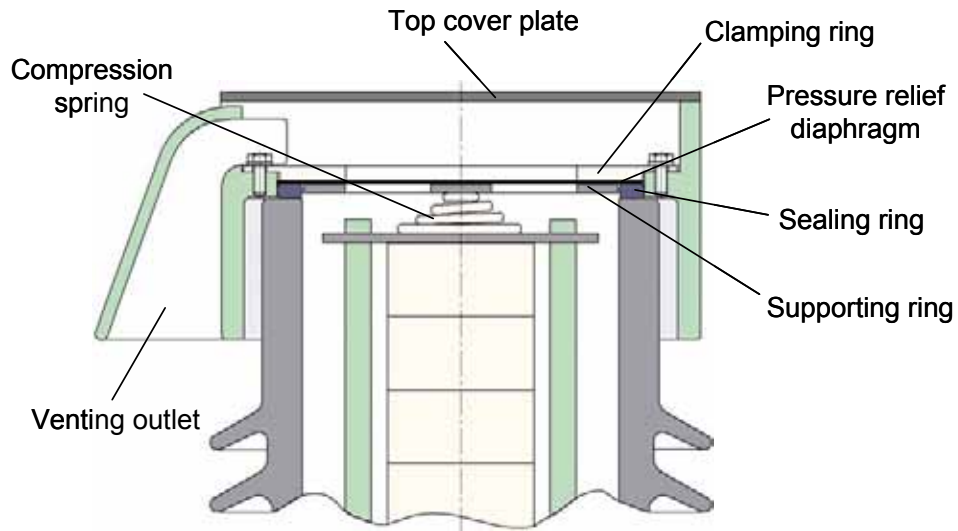


Fig. 11: Sealing system of a high-voltage porcelain housed MO arrester

The pressure relief diaphragm, which is used in this arrester construction, consists of very pure high grade steel or nickel material, which is only a few tenths of a millimeter thick. In terms of the design and the quality assurance, it is challenging to make the diaphragm resistant to corrosion for a period of 30 years. The diaphragm is pressed against the sealing ring with a metal **clamping ring** screwed to the flanges. It is especially important to make certain that only compatible (with respect to electro-chemical processes) material combinations are used. Otherwise gap corrosion will definitely result, which sooner or later will lead to leakages.

The particular advantage of the pressure relief diaphragm¹ is its extremely short opening time in the case of an arrester overload. An arrester overload is a very infrequent occurrence². It cannot, however, in principle be ruled out, not even in the case of an overdimensioned arrester. Possible causes for this are, for example, direct lightning strikes occurring near the arrester, or power-frequency voltage transfer from a higher to a lower voltage system, for example, on a transmission line with several voltage levels which cross each other because of a conductor failure or galloping. In such a case an

¹ Other types of pressure relief devices are also common, for example, spring loaded covers.

² In high-voltage systems this occurs considerably less than in a distribution system.

overload of one or several of the MO resistors occurs in the affected arrester. A partial arc builds up, which in split seconds turns into a complete arc between the two flanges inside the housing. The full short-circuit current of the net, which appears where the arrester is actually installed, flows through this arc (root-mean-square value up to about 80 kA, peak value up to about 200 kA). As a result, an abrupt increase in pressure develops within the housing. At the same time, the pressure relief diaphragm tears open within a few milliseconds, thereby ensuring a safe pressure relief before the bursting pressure of the housing is reached. The hot pressurized gases very rapidly escape from the inside of the housing through the two **venting outlets** ("venting" of the arrester). Outside the housing the two gas streams meet and cause the arc that was burning inside the housing, to commute and continue burning outside the arrester, until the failure has been cleared. Up to that point, breaking of the porcelain¹ can still occur as a result of the extreme thermal stress. However, because of the practically unpressurized decay, no other serious damage can ensue.

When the arc burning inside the housing is quenched as a result of a system fault clearing, which already occurs before the opening of the pressure relief diaphragm, or when the pressure build-up occurs relatively slowly, because of a very low fault current (which occurs especially in resonant earthed neutral systems), the pressure relief diaphragm does not rip, but instead only pulls wrinkles, which (in this case, intentionally) leads to leakage². This makes it impossible for a failed arrester to be under internal pressure of more than one bar and greatly reduces the security risks when dismantling a defective arrester.

The most important components of an MO arrester have been described above, employing a high-voltage arrester with porcelain housing as an example. However, a few other details are necessary to complete the description of a high-voltage arrester (**Figure 12**).

It has already been mentioned that starting at a certain length of the MO resistor column, an arrester is no longer manufactured in one piece. The longest a porcelain hous-

¹ A so-called thermal or secondary breaking, which is expressly permitted according to the arrester standards.

² Such a defective arrester is recognizable from the outside by the heavy layer of black carbon on its housing.

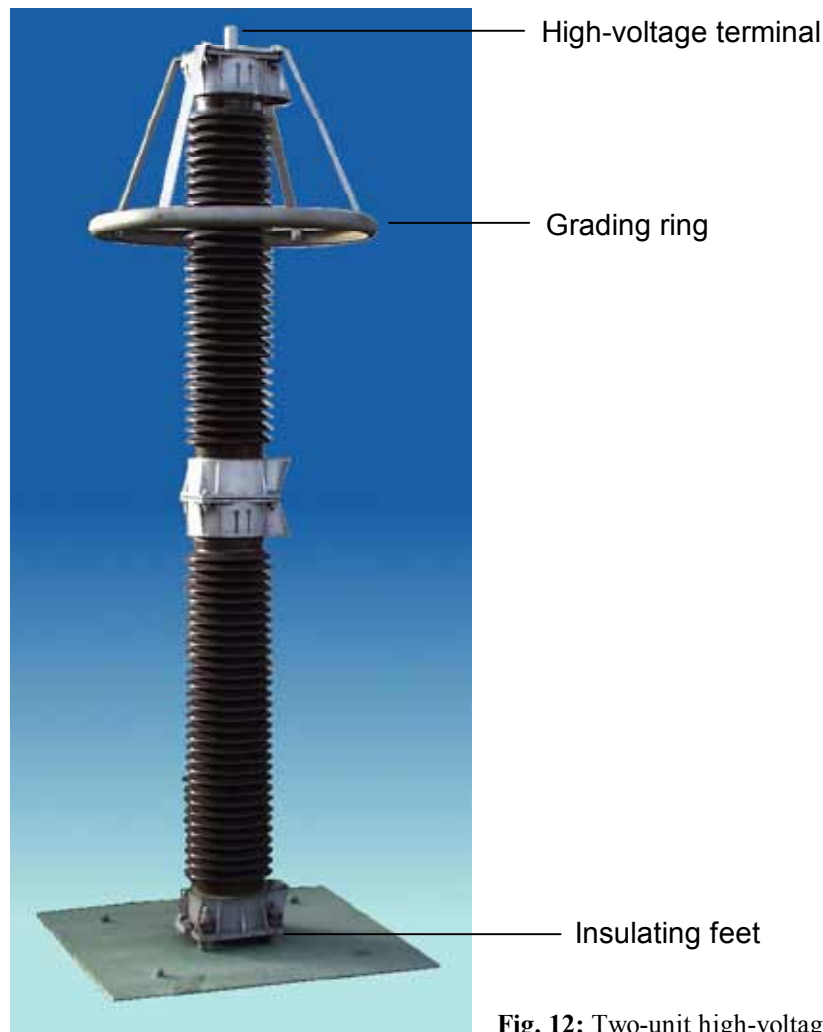


Fig. 12: Two-unit high-voltage arrester

ing can reasonably be, is, for technical and economical reasons¹, about two meters. At this length an arrester can be accommodated in one single unit for a solidly earthed neutral 245-kV-system, as long as creepage distance requirements are not higher than average. At all higher voltage levels, the arrester must consist of several units, for example in a 420-kV-system it would have at least two parts. At the higher voltage levels or when there are extreme creepage distance requirements, it can also be made up of three, four or five parts. In principle, there is no upper limit, as long as the arrester still proves to have sufficient mechanical properties.

Starting at a length of about one and a half to two meters on up, and usually for arresters made up of several units, grading rings are absolutely essential. These serve to

¹ One of the reasons is that the longer the housing, the lower the short-circuit withstand capability becomes. Another is that most porcelain insulator manufacturers cannot fire the greater lengths in one piece.

control the voltage distribution from the high-voltage end to the earth end, which is unfavorably influenced by the earth capacitances affecting the arrester. Without the appropriate countermeasures the MO resistors at the high-voltage end of the arrester would be stressed considerably more than those at the earthed end, resulting in potentially excessive heating. Grading rings differentiate from each other in terms of their diameters and in the lengths of their fixing braces. The rule of thumb in this case is as follows: the larger the diameter and the longer the braces, the better the control effect is on the voltage distribution. At the same time there are two reasons for keeping both of the sizes mentioned small, if at all possible:

- The relevant standards on erecting electrical power installations¹ stipulate a minimum distance between the conductors of the neighboring phases. These requirements are also valid for the distance between the grading rings of two neighboring arresters. The smaller the grading ring, the smaller the centerline spacing of neighboring arresters can be, and thus the bay width to be selected.
- The fastening braces cannot be lengthened to whatever size desired, since the empty arrester housing must fulfill certain withstand voltage requirements. If the braces are too long, flashovers may occur from the grading ring over the neighboring flange to the earth, or directly to the earth, especially while testing with [switching impulse voltage](#).

Users sometimes regard grading rings as an inconvenience because they occupy space in the switchyard. However, it is extremely important to ensure that the grading rings specified and supplied by the manufacturer are installed. If this is not done, thermal instability with resulting failure of the arrester may occur.

Grading rings must not be confused with corona rings, which are sometimes specified for extra-high voltages in order to provide an electrostatic shield for the terminals so as to adhere to the maximum permitted interference voltage values.²

High-voltage station arresters are usually not directly earthed; instead monitoring devices, such as [surge counters](#), [monitoring spark gaps](#) or [leakage current indicators](#) are connected with the arrester in series. In this case insulation is provided for by setting the

¹ For example, the European harmonization document HD 637 S1, or the standard IEC 61936-1: Power installations exceeding 1 kV a.c. – Part 1: Common rules.

² See the section entitled "Grading ring" in the appendix for more details about grading rings and corona rings.



Fig. 13: Bottom flange with insulating feet and leakage current monitor

arrester up on **insulating feet** (**Figure 13**). Earthing then occurs through the appropriate monitoring devices. The insulating feet must be mechanically designed in such a way, that they can withstand long-term as well as short-term mechanical forces affecting the arrester. They must have adequate electrical strength, so that they do not flashover under the stress of the voltage drops across the monitoring devices situated in parallel and caused by the self-inductance of the ground connection.

The ground connection lead should have a cross section of at least 35 mm², less for electrical reasons – for this a smaller value would be entirely adequate – than for reasons of mechanical strength and resistance against environmental impact.

The **high-voltage terminal** serves as the connection to the overhead line conductor. Normally bolts and flat terminals are used (**Figure 14**). Their design and dimensions are standardized, for example in accordance with [DIN](#) or – in the United States – with [NEMA](#). However, special customer-specific variants are also common.



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

The following pictures (Figures 15...17) show other models of MO arresters: a medium-voltage distribution arrester with polymer housing and two different designs of high-voltage arresters with polymer housing. The chosen examples differentiate from each other, in some cases greatly, in their design features, and thus provide an overview of some of the basic arrester designs in use. Medium-voltage arresters with porcelain housing are not discussed in more detail here as they have been almost completely superseded by arresters with polymer housing. Millions of them are nevertheless still in use. The appendix contains a diagram.

Due in large part to the failures caused by leakage in cheaply designed distribution arresters with porcelain housings, the first ones equipped with polymeric outer insulation appeared on the market in the mid 1980's. Their most remarkable design feature is the polymer housing located directly on the MO resistor stack. As a result, the gas-filled gap between the MO resistors and the housing no longer exists, and with the appropriate constructive realization of the interface between the polymer housing and the end fittings, a sealing system can be completely omitted. Similarly, in case of an overload, a pressure buildup and the related risk of housing breakage can be avoided. Nevertheless, a number of different designs are possible based on this principle¹.

In the case of a porcelain insulator, different properties – such as, protection from environmental impact and provision of sufficient creepage distance on the one hand, and mechanical strength on the other – are united in a single component. In an arrester with polymer housing, however, these properties are apportioned to two different components. Mechanical strength is, virtually without exception, achieved with fiber-glass reinforced plastic (FRP) materials. In the example shown in **Figure 15**, several rods serve this purpose. They are strained, e.g. by crimping, in the end fittings and enclose the MO resistor stack like a cage. That is why the term "cage design" is used in this context². Here, the MO resistors themselves form part of the mechanical structure. This is how a mechanical high-strength unit out of MO resistors, end fittings and the FRP structure are created. This module is inserted in a mold, in which silicone rubber is directly injected. With the appropriate manufacturing techniques, it is possible to obtain a

¹ Note that the arresters built according to this principle are not "per se" moisture tight and break resistant in case of overloading, as was anticipated in the beginning. With these arresters specific design characteristics and the quality of manufacturing also continue to play an important role.

² Another common version uses mats or bands wrapped onto the MO resistors. After the resin within these mats is cured, it forms a stiff tube which directly bonds to the MO resistors. This design is often called the "wrapped design".

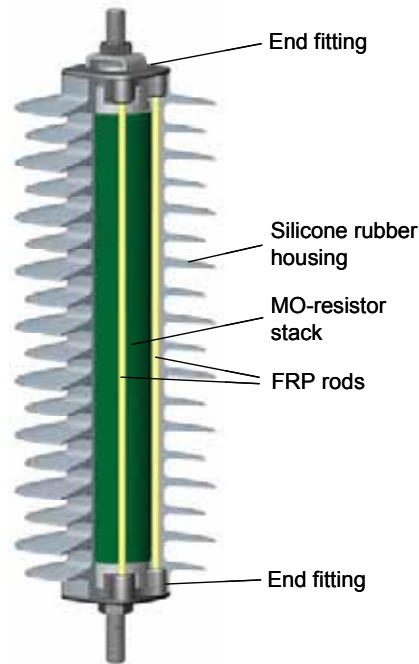


Fig. 15: Cross-sectional drawing of a polymer-housed MO distribution arrester

perfect bond of the silicone rubber with the other components, void-free and permanent. The final product is all of a piece. One advantage of the applied silicone rubber in this case, in comparison to cheaper materials, which are also used, is the excellent endurance properties – by now, it is possible to fall back on about 40 years of service experience in this area. Another advantage is a characteristic unique to silicone rubber, [hydrophobicity](#): even if the silicone surface is heavily polluted, water simply drips off. This suppresses the formation of conductive layers and advantageously affects the operational performance of the arrester in polluted conditions.

The risk of the housing bursting and splitting in case of an arrester overload for the design shown in Figure 15, is nonexistent. The arc resulting from a puncture or a flash-over of the MO resistors rips the silicone rubber housing open, and with almost no resistance, finds its way outside.

The advantages of such an arrester design have only been hinted upon here. The combination of the given weight reduction in comparison to a porcelain housing, the ease of handling during transportation and installation, and last but not least, the savings in cost that manufacturing such an arrester offers in comparison to an arrester with porcelain housing, present advantages which make it clear why the polymer-housed arresters within the medium voltage range have become so popular. As a result, it is also apparent why the devices with porcelain housings have, in this case, virtually disappeared from the market.

A peculiarity of distribution arresters is their frequent application in connection with [disconnectors](#). This additional device can be not only integrated in the arrester, as depicted in **Figure 16**, but also be attached to its outside, and is often of great importance for a trouble-free operation of a distribution network. Here the locations of the arresters



Fig. 16: Polymer-housed MO distribution arrester with disconnector and insulating clamp

are not limited to only a few switchyards or substations, as in a high-voltage transmission system. Instead arresters are distributed throughout the whole net (pole stations, cable terminations), and in many cases an arrester which has broken down is not noticeable within this great spatial expanse. And even if it is, replacements cannot always immediately be made. The disconnector is supposed to ensure that, after a possible failure, the arrester is separated from the network. Otherwise the arrester could, after such an incident, form a permanent earth fault. In that case, the arrester must obviously be fitted with an insulating clamp as shown in Figure 16. The insulating clamp is dimensioned to withstand the line-to-earth voltage (after failure, the arrester is practically a short-circuit) for a certain period – a requirement that is not always easy to meet. It should, however, also be mentioned that the disadvantage of a disconnector is that as a result of using it, arrester failures may remain unnoticed, and overvoltage protection at this point might unintentionally not be attained. Therefore, for the use of disconnectors no general recommendations can be given. They are used less frequently or sometimes not at all in resonant earthed neutral systems, which can be operated over longer periods of time under earth fault conditions. They are, however, used more frequently in solidly earthed neutral systems. Individual cases depend greatly upon the system management of the different utilities.

The principle of the cage design has also been applied to high-voltage arresters. See **Figure 17** for an example. To achieve adequate mechanical strength and a high short-

circuit withstand capability, the FRP cage contains considerably more rods than on a medium-voltage arrester. Otherwise, the design features are the same. To use this design with higher voltage levels, multiple modules are simply lined up.

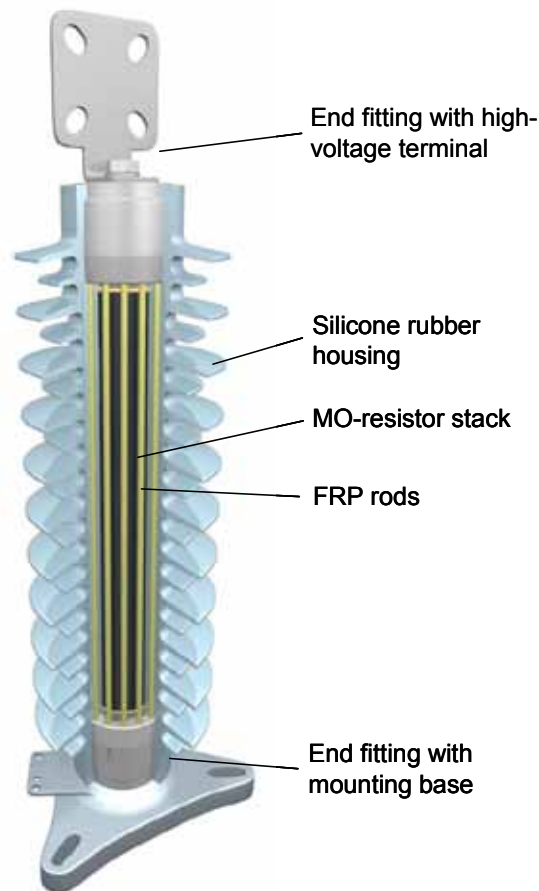


Fig. 17: Cross-sectional drawing of a polymer-housed MO high-voltage arrester of "cage design"

It is significantly more difficult for this design to meet the mechanical requirements at the extra-high voltage levels and the new ultra-high voltage levels (UHV: $U_s > 800$ kV) in particular. For example, the deflection under load is no longer trivial and may cause problems. Above a certain overall length, the arrester can only be installed in a suspended position with a moving support. In addition, the high voltage levels often require a number of MO resistor columns to be connected in parallel, which can be very costly because entire arresters, together with their housing, must be arranged alongside each other. In this case, a structure that was introduced in the late 1980s may be used, as illustrated in **Figure 18**. This high-voltage arrester with polymer housing uses a composite hollow core insulator, as used with instrument transformers and bushings. To distinguish this design from other arresters with polymer housing, it is also known as the "tube design". One notices immediately that, in principle, this has the same design as the one in Figure 8. Indeed, essentially only the porcelain insulator has been replaced

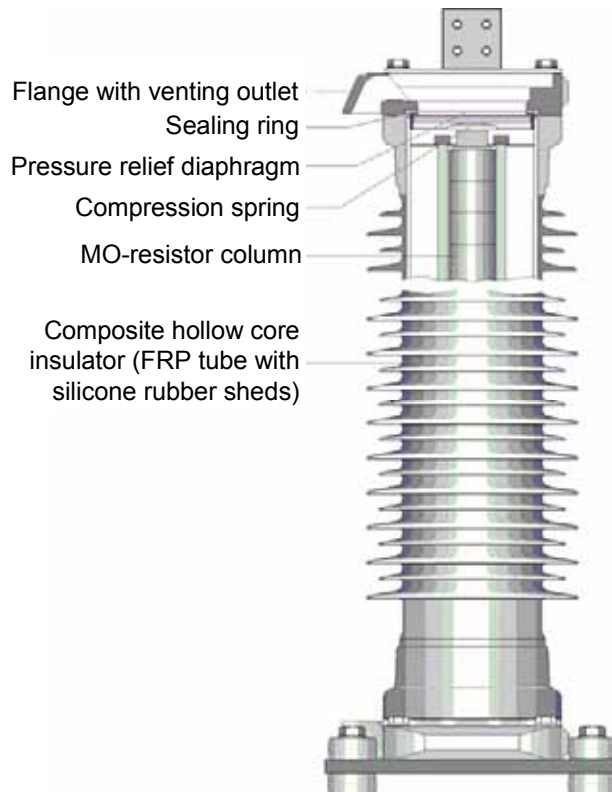


Fig. 18: Cross-sectional drawing of a polymer-housed high-voltage arrester of "tube design"

with a [composite hollow core insulator](#). The composite hollow core insulator is made up of an FRP tube on which the sheds – practically only ever made out of silicone rubber – are [directly molded](#) on, or [pushed on](#) and [vulcanized](#) in the form of individual prepared sheds. This design principle offers some considerable advantages for applications up to the highest voltage levels. Since the inner structure of an FRP tube (for example, relative content of glass fibers, or the winding angle of the fibers), its wall strength and its diameter can, within a large range, be selected without restrictions, such a tube can be endowed with almost any mechanical property. As a result, to name just a few, it can be optimized with respect to tensile strength, bending strength, or internal pressure strength. Thus, it is possible to design high-voltage arresters, which are so mechanically strong, that they can endure the most severe earthquakes intact and at the same time be used as a post insulator in a substation.

The application last mentioned is of benefit to another property only found in this design: in the case of an arrester overload, it is certain that with this construction a housing breakage will never occur; not even any of the inner parts will be ejected. The tube will remain almost completely intact, and as a result it offers the best possible safety for the whole switchgear in a substation (see also the section on designing arresters).

The higher costs of the composite hollow core insulator of such a design, in comparison to porcelain insulators, has long been an obstacle to its being further distributed. As distribution of composite hollow core insulators increases, along with the corresponding market supply, a resulting acceptance of the technology is likely to change the situation in favor of this technology. Anyway, in certain applications, independent of the costs, this design is virtually without alternatives.

To conclude, current development trends clearly point to polymer-housed arresters at all voltage levels. At medium voltages, the process is more or less complete. At the high and extra-high voltage levels, these changes will take more time because the investment costs are higher and the acceptance of new technologies is generally lower (due to the higher risks). However, even in this area, the proportion of polymer-housed arresters is growing at the expense of porcelain housings, thanks to the obvious cost and technology benefits.

Configuring MO Arresters

In order to configure an MO arrester, it is first of all necessary to understand how the different requirements and parameters affect the operational performance of the arrester. With knowledge of the basic principles and interdependencies, it is then possible to lay out an appropriate arrester for less common applications. This chapter describes the general approach and concludes with simple sample calculations to select typical arresters for overvoltage protection in a.c. distribution and transmission systems at voltage levels between $U_s = 24$ kV and $U_s = 420$ kV. The arresters are always connected phase-to-earth ("phase arrester"). The configuration of arresters in order to protect the neutral point of a transformer ("neutral point arrester") is also discussed briefly.

The description is given only in view of the device, in other words, so that the question of how an arrester should be configured is answered in a way that, on the one hand, it fulfills its protection requirements and on the other, does not become a problem itself. However, the application will not be discussed here, as to where in the system or on which equipment the arrester should be applied to. For this, the appropriate IEC publications 60071-1 and 60071-2 on insulation coordination or the selection and application recommendations for surge arresters, IEC 60099-5, can be consulted.

This chapter refers to the relevant international standards for testing and application of metal-oxide surge arresters without gaps: IEC 60099-4 and IEC 60099-5. The corresponding American (IEEE) testing standard C62.11 and application guide C62.22 are listed at the end of this handbook, but they are not used here. They continue to differ in some respects more or less significantly from the relevant IEC publications, although efforts are underway to harmonize the two sets of standards.

For the most part, the requirements for an MO arrester can be traced back to two basic requirements. On one hand arresters should provide adequate protection, and on the other they should be laid out for stable continuous operation. Adequate protection means that overvoltages at the device to be protected must always remain below its withstand voltage, with a sufficient safety margin. Stable continuous operation means that the arrester must be able to handle all long-term, temporary or transient stresses which result from network operation, while remaining electrically and thermally stable under all conditions.

Both basic requirements cannot be fulfilled independently. A reduction of the protective level automatically means a higher specific electrical stress during continuous

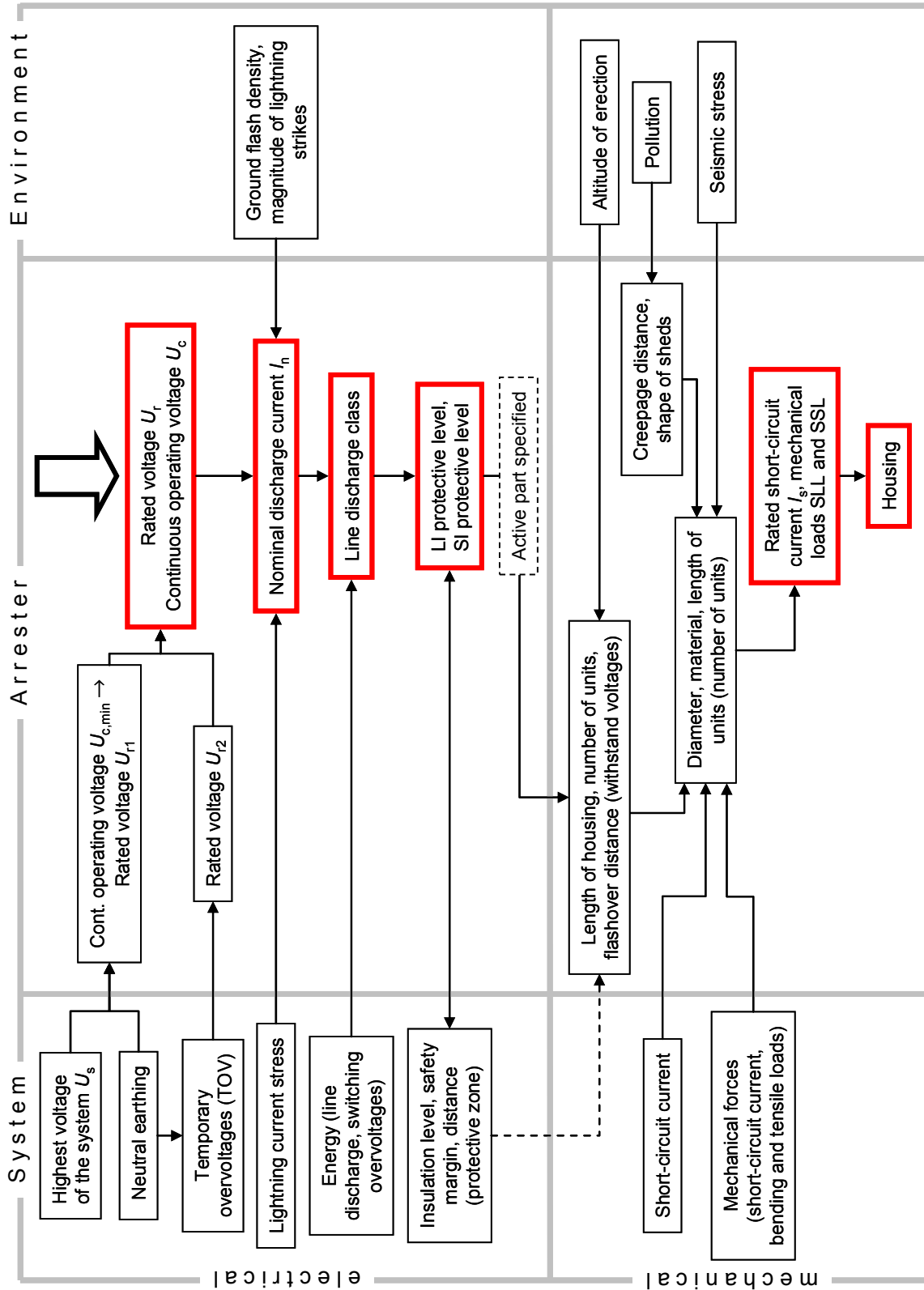


Fig. 19: Procedure for configuring an MO arrester

operation, and conversely, the continuous operating voltage of an arrester cannot be increased arbitrarily without raising its protective level as well. Both operating points are – at least for a given type of MO resistor – strictly associated with each other through the voltage-current (U - I) characteristic curve.

Additional requirements involve the electrical characteristics of an arrester: they should not change during its life span, and insensitivity to environmental influences, such as pollution, solar radiation or mechanical strain, must be maintained.

In **Figure 19** a flow chart illustrates an approach to configuring an arrester. In this case a high-voltage arrester is depicted, since, in comparison to a distribution arrester, more and higher demands are made here. The steps shown in the picture will be discussed below in more detail in the sequence in which they are carried out.

Choosing Continuous Operating Voltage U_c and Rated Voltage U_r

So that the arrester can protect safely, it must be able to work absolutely soundly in continuous operations. Thus, the first step is to establish a minimally required continuous operating voltage $U_{c, \min}$. As already mentioned in connection with Figure 2, this must be as high as the continuous phase-to-earth voltage of the system, provided with at least an additional 5%. The allowance takes into account possible harmonics in the system voltage, which may increase its peak value¹.

Here "continuously" applied voltage means every voltage that occurs within an uninterrupted period of more than 30 minutes. For this reason to determine the continuous operating voltage, the type of neutral earthing of the system is decisive. In isolated or resonant earthed neutral systems², the voltage of a healthy phase against ground takes on the value of the phase-to-phase voltage in the case of a one-phase earth fault ([earth fault factor \$k = 1.73\$](#)). Since resonant earthed neutral systems are operated quite commonly for time periods of more than 30 minutes in this condition, the continuous oper-

¹ Because of the extreme non-linearity of the U - I -characteristic, the r.m.s. value of power-frequency voltage plays less of a role than its peak value, which can overproportionally increase the resistive component of the leakage current periodically at the moment of the voltage peak.

² Resonant earthed neutral systems are mainly found in central Europe, from the medium voltage range up to the 170-kV-level. Systems at higher voltage levels in general have solidly earthed neutrals.

ating voltage of the arrester must, in this case, have the value of the highest voltage of the system, U_s . Only the additional five percent is not taken into consideration here:

Solidly earthed neutral system:

$$U_{c, \min} \geq 1.05 \cdot U_s / \sqrt{3}$$

Isolated or resonant earthed neutral system:

$$U_{c, \min} \geq U_s$$

With the pre-selection of the minimally required continuous operating voltage, a factor which usually has a value of 1.25¹ – there are, of course, exceptions – helps in achieving a rated voltage $U_{rl} = 1.25 \cdot U_{c, \min}$. This is the lowest necessary, though not final, rated voltage of the arrester:

Solidly earthed neutral system:

$$U_{rl} \geq 1.25 \cdot 1.05 \cdot U_s / \sqrt{3}$$

Isolated or resonant earthed neutral system:

$$U_{rl} \geq 1.25 \cdot U_s$$

It is clear from these two relationships that the minimally required rated voltage of an arrester in the solidly earthed system is 76% of the (phase-to-phase) system voltage or 125% in an insulated or compensated system. The required rated voltage can, however, also be reached by taking a completely different approach, namely by examining the temporary overvoltages which may occur in the system. The special case of a system, which is operated with a resonant earthed or isolated neutral, and in which the temporary overvoltages are directly decisive for the continuous operating voltage, has already been mentioned. On the other hand, in the case of solid neutral earthing, the temporary overvoltages may reach values of up to 1.4 times the maximum phase-to-earth voltage (earth-fault factor $k \leq 1.4$) for a time period from a few tenths of a second to up to several seconds. Power-frequency voltage above its continuous operating voltage can only be applied to an arrester for a limited period of time: the higher the voltage, the shorter the permissible time of application is. This correlation is depicted in the [power-frequency voltage versus time](#) or U - t -characteristic (**Figure 20**). This indicates the ratio of the permissible power-frequency voltage and the rated voltage U_r , both given as r.m.s. values, over time, represented in logarithmic standards. The ratio is called the factor k_{tov} . In this case it is assumed that the arrester is in an unfavorable state, that is, that the arrester has previously been heated up to 60 °C, and directly before the application of

¹ There are no direct physical reasons for the value of 1.25; it was a purely empirical result, which occurred during the manufacturer-independent development of practically all types of MO arresters.

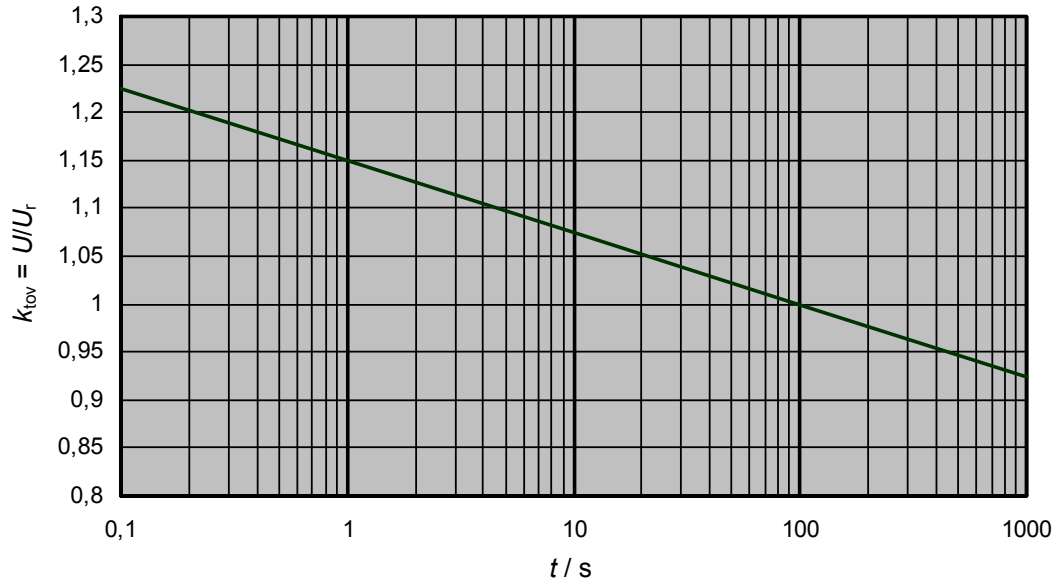


Fig. 20: Example of a power-frequency voltage versus time (U - t) characteristic

power-frequency voltage it had to absorb its full rated thermal energy. From Figure 20 it is clear that under these conditions the rated voltage U_r may be applied for a time period of 100 seconds¹. The ten-second-voltage is, on the other hand, 7.5% above the rated voltage and the one-second-voltage already 15% above. The U - t -characteristic is applied in the following manner: the voltage value U_{tov} , which occurs in a system for a time period of 1 s, would, for example, be known. This voltage value must correspond, according to the U - t -characteristic curve, to 1.15 times the arrester-rated-voltage ($k_{tov} = 1.15$). In other words, the possibly chosen rated voltage of the arrester, U_{r2} , is the occurring 1-s-voltage value divided by a factor k_{tov} , which is valid for a time period of one second, in this case, therefore, $U_{r2} = U_{1s} / 1.15$. In general this reads as:

Solidly earthed neutral system:

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

If further sets of temporary overvoltage values and the time of their occurrences are available as a result of knowing the systems conditions, then for each one the corresponding rated voltages must be determined separately. If no information is available at all, then in the case of a solidly earthed neutral, an earth-fault factor of 1.4, and a time period of ten seconds should be assumed for the occurrence of temporary overvoltages.

¹ In the [operating duty test](#) (during the type test) the rated voltage need only be applied for a duration of 10 seconds. The 100 seconds in this case provides additional security.

The highest value of the different rated voltages determined from the temporary over-voltage conditions as described above, is the rated voltage U_{r2} in Figure 19. Only a small step is now needed to determine the final rated voltage of the arrester – U_r is the higher of the two values U_{r1} and U_{r2} , rounded up to the next highest value divisible by three¹:

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

rounded up to a value divisible by three

If the rated voltage U_{r2} is greater than U_{r1} , then the continuous operating voltage must obviously be redefined:

$$U_c = U_r / 1.25$$

After determining the continuous operating voltage and the rated voltage in this way, the arrester is then generally designed not only for a stable normal continuous operation, but also for all temporary overvoltage conditions in the system. It is, however, recommended that a somewhat higher rating than the described minimal rating is selected, as long as the protective level of the arrester does not, as a result, become unjustifiably high. In most cases the protective level requirements allow for this². A higher rating increases the stability of the arrester and provides additional safety, for example in a heavily polluted environment, or when unexpectedly higher temporary overvoltages occur. For this reason one normally finds arresters in the systems which have continuous operating and rated voltages higher than the minimally required ones. However in each case this greatly depends on the utility's individual system management.

¹ The standard IEC 60099-4 refers to steps in which the rated voltages are to be stated. These are between 1 kV and 24 kV, depending on how high the rated voltage is. At the same time other steps are permitted, as long as it results in a rated voltage which is divisible by 6. Currently even finer steps, e.g. 3 kV, are also offered for the highest rated voltages.

² An exception is found in the systems at the highest voltage levels, $U_s \geq 550$ kV. Demands for lower switching impulse protective levels normally limit the amount that the rated voltage can be raised above the minimally required value. Also see the examples at the end of this chapter.

Selecting the Nominal Discharge Current I_n

The nominal discharge current I_n serves to classify an MO arrester. From a technical point of view it is calculated from a typical maximum lightning current amplitude that can be expected in the substation, for which the insulation coordination is performed via the arrester's lightning protection level. This amplitude is calculated from the flashover voltage U_{fo} of the line insulators, the lightning protection level U_{pl} of the arresters and the surge impedance Z of the line for $I_{\max} = (2 \cdot U_{fo} - U_{pl})/Z$. In this equation, the factor 2 reflects the fact that according to the rules of traveling wave processes, the lightning current reaching the substation doubles in the arrester because the arrester is approximately equivalent to a short-circuited line termination (with a constant voltage source in series). Here is a worked example for a 420-kV-system: $U_{fo} = 2.1$ MV, $U_{pl} = 806$ kV, $Z = 350 \Omega \rightarrow I_{\max} = 9.7$ kA.

IEC 60099-4 currently specifies five different values¹, which belong to different ranges of rated voltage:

Table 1: Nominal discharge currents according to IEC 60099-4

1.5 kA	2.5 kA	5 kA	10 kA	20 kA
under consideration	$U_r \leq 36$ kV	$U_r \leq 132$ kV	$3 \text{ kV} \leq U_r \leq 360$ kV	$360 \text{ kV} < U_r \leq 756$ kV

These values, however, do not directly reveal anything about the operating characteristics. Thus, for example, a 10-kA-arrester can readily withstand lightning current impulses of higher amplitudes without sustaining damage. The actual function of these classifications is to specify different further demands and test requirements, depending on their class.

For distribution arresters, which are mainly used with classes 5 kA and 10 kA, the nominal discharge current represents a real differentiating characteristic. When carrying out an [operating duty test](#), the energy into a 5-kA-arrester is injected in the form of two [high current impulses](#) of 65 kA each, after it has previously been [conditioned](#) with 20 lightning current impulses of 5 kA (which is its nominal discharge current). With the 10-kA-arrester, on the other hand, the appropriate value of the high current impulses is 100 kA, and the value of the lightning current impulses is 10 kA. Since this means a

¹ From IEC 60099-4, Table 1. The IEC standard lists values in "A", i.e. 10 000 A instead of 10 kA. However, "kA" is now more widely used in practice.

considerable energetic stress for the small MO resistors (with diameters in the range of less than 30 mm to up to 45 mm), as are used for distribution arresters, a 10-kA-arrester must indeed be equipped with larger volume MO resistors than those needed for a 5 kA type, in order to pass this test. For central European distribution systems, 5-kA-arresters are completely adequate. Only in exceptional cases (e.g., because of an above average [keraunic level](#)) is the use of 10-kA-arresters recommended. In practice the 10-kA-arrester is becoming ever more common, as the price difference between the two types diminishes, while at the same time there are logistic advantages to using only one arrester type for the entire system.

For high-voltage arresters only two classes, 10 kA and 20 kA, are appropriate. According to the table above, the use of a 5-kA-arrester would also be feasible in a 170-kV-system; however, in practice, it is uncommon. Also, the application guide IEC 60099-5 recommends the 5-kA-arrester for voltages of only up to $U_s = 72.5$ kV.

A main difference between the two classes, 10 kA and 20 kA, is the [line discharge class](#) which they can be assigned to: for a 10-kA-arrester, it is classes one to three, for a 20-kA-arrester, classes four and five. Accordingly, different 10-kA-arresters can have very different operating characteristics, and the actual classifying characteristic is not so much the nominal discharge current, as the line discharge class. 10-kA-arresters of line discharge class 3 can generally be used in systems with levels of up to and including 420 kV without any problems. However, 20-kA-arresters are also utilized at this voltage level, sometimes while using the same MO resistors. It is, however, for the most part not technically necessary.

Selecting the Line Discharge Class

The line discharge class is the actual determining characteristic of a high-voltage arrester. Presently it is the only way of specifying the energy handling capability of an arrester in accordance with IEC 60099-4. It is, however, only indirectly found within the value of the line discharge class. The relationship is relatively difficult to understand. This has, in the end, prompted almost all the manufacturers to include more de-

tails on the energy handling capability in their catalogues, than those provided in IEC standards¹.

The definition of the line discharge class is based on the assumption that a long transmission line, charged to a certain overvoltage during a switching operation, will discharge into a connected arrester in the form of a [traveling wave process](#). Assuming the equivalent circuit diagram of a line is an iterative network of [\$\pi\$ -elements](#), formed by inductances and capacitances, the current will flow at a value which is determined by the voltage value and the surge impedance of the line, for a duration given by the length of the line and the propagation speed of an electro-magnetic wave. Ideally, it adjusts to a rectangular-shaped current impulse. This process must be simulated in a laboratory in a [line discharge test](#). In this case the current impulse is normally generated with the help of a [distributed constant impulse generator](#), which is nothing more than the line simulation made up of a series connection of a finite number – about 10 to 30 – of π -elements. The IEC standard 60099-4 now defines five different line discharge classes. Increasing demands are made on the arrester from class one to class five, in which the electrical parameters of the impulse generator are established for the test:

Table 2: Line discharge classes and associated testing parameters in IEC 60099-4

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

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

These parameters are derived from typical characteristic values of high-voltage transmission lines². No direct conclusions about the energy stress which is imposed on

¹ The line discharge class system actually was first used for gapped arresters with current-limiting series gaps. At the beginning of the 1980's – when MO arrester technology was still in its infancy – a testing standard for MO arresters was developed, and the existing system was adopted, since there were no better alternatives. After such a system is introduced, it is difficult to change it again. In the standardization process, new definitions for energy handling capability are, however, being considered, which are more appropriate for stresses associated with today's arrester applications.

² Also see IEC 60099-1, Table C.1 or IEC 60099-5, Table 1.

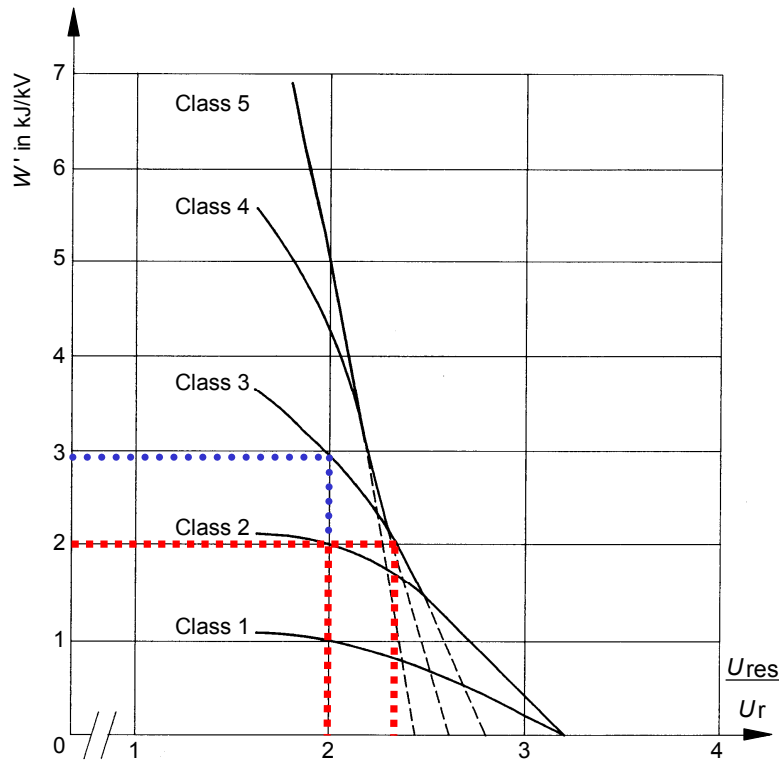


Fig. 21: Specific energy in kJ/kV of rated voltage dependent on the ratio of switching impulse residual voltage U_{res} to the r.m.s. value of the rated voltage U_r of the arrester (from IEC 60099-4)

the arrester during a test can be drawn from this table. For that reason the IEC standard 60099-4 provides an additional diagram which represents the converted energy in a test object, with reference to its rated voltage¹, which occurs during a single line discharge². This energy is not a fixed value, but instead depends on the arrester protective level, or more precisely, on the switching impulse residual voltage U_{res} with the smaller switching current impulses from Table 5. The higher the residual voltage, the less energy the arrester absorbs during the line discharge, since the line will discharge less intensely when the residual voltage is higher. The diagram referred to is depicted in **Figure 21**. It is now possible to easily identify the problem when the energy handling capability is specified with the help of the line discharge class. If MO resistors are applied with a

¹ It is common – in the standard IEC 60099-4 as well – to use the rated voltage when referring to specific energy. Some manufacturers, however, use the continuous operating voltage as the reference value, due to, among other things, the fact that the rated voltage is not defined in the US arrester standard, IEEE C62.11 (instead, a "duty cycle voltage rating" is specified there, whose definition is different from that of the rated voltage in the IEC standard).

² During the [switching surge operating duty test](#), which has to be performed on arresters of line discharge classes 2 to 5, the test object is subjected to **two** of these discharges within an interval of about one minute. That means an arrester must be able to absorb at least twice the amount indicated in the diagram, without becoming thermally unstable.

given amount of specific energy handling capability, then the arrester can, depending on the residual voltage it has, be assigned to different line discharge classes. The following example proves this (the red dashed lines in Figure 21): when using MO resistors, which can absorb 2 kJ/kV of energy per line discharge (i.e., double the value, namely 4 kJ/kV, during the operating duty test – performed with two successive line discharges – without becoming thermally unstable), the arrester has a line discharge class of two at a ratio of $U_{\text{res}}/U_r = 2$. However, with the same MO resistors it already can be assigned to line discharge class three at the ratio of $U_{\text{res}}/U_r = 2.35$. But the seemingly "better" arrester with the line discharge class of three might possibly be worse for the planned application, since its protective level is higher! In order to reach the line discharge class of three while maintaining a ratio of $U_{\text{res}}/U_r = 2$, MO resistors must be used with an energy handling capability of almost 6 kJ/kV (about 3 kJ/kV per discharge: the blue dotted lines in Figure 21), that means those with greater diameters.

Inversely, one can only draw conclusions from the line discharge class in connection with the residual voltage as to the energy handling capability of an arrester, and thus about the used MO resistors. It is important to make these interdependencies clear when selecting an arrester.

As long as there are no particularly easy or difficult requirements originating from the system, the following line discharge classes, depending on the system voltage, are recommended (IEC 60099-5):

Table 3: Guide values for line discharge classes depending on system voltage

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

In practice, however, one frequently tends to select the next higher line discharge class, respectively, in the table. That leads to the problem of current line discharge class five frequently not meeting the demands of the extra-high-voltage systems with $U_s > 550 \text{ kV}$. In fact, at this voltage level, and sometimes even at the 550-kV-level itself, MO resistor diameters and/or parallel connections of resistors are used, which yield much greater energy handling capability than is necessary for line discharge class 5. For these systems it is, however, common to determine the requirements on the energy

handling capability with detailed system studies, so that an exact value for the energy handling capability, instead of the line discharge class, is specified by the user here.

When deciding on a definite line discharge class – and thereby indirectly on a definite energy handling capability – the required MO resistor diameter has also automatically been selected. The following classification is a rough orientation:

Table 4: Typical assignment of MO resistors to line discharge classes

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

After determining the rated voltage and subsequently choosing the MO resistor diameter, the protective characteristic of the arrester has been completely established. All residual voltage values result from the U - I -characteristic of the selected type of MO resistor. The next step is to check whether the retained protective characteristic is adequate.

Selection and Review of the Protective Levels

The protective characteristic of an arrester is most frequently assessed by means of its lightning impulse protective level. That means it is assessed according to its residual voltage while the nominal discharge current is flowing. As already mentioned, according to the application guide of insulation coordination, IEC 60071-2, there must be a factor – the so-called [safety factor](#), K_s – of at least 1.15 between the standard lightning impulse withstand voltage (“BIL”) of the device to be protected with a non-self-restoring insulation, and the highest lightning overvoltage which is expected to occur at its terminals. In this case it should be noted that, due to traveling wave processes and inductive voltage drops, the voltage at the terminals of the device to be protected can generally be higher than the voltage directly at the arrester terminals. Besides that, it should also be noted that – though very unlikely in high-voltage transmission systems – the discharge current may be higher than the nominal discharge current of the arrester.

If the distance between the arrester and the device is not too great – arresters have a [protective zone](#) of only a few meters in a distribution system and up to about sixty me-

ters in high- and extra-high-voltage systems – this normally means that a protective level equal to the standard lightning impulse withstand voltage of the device to be protected, divided by a factor of 1.4, is adequate in protecting against lightning overvoltages. It should, however, be kept in mind that this simplification might not be adequate for special system configurations and cases of application, or when the distance between the arrester and the device is great. Thus, the correct and standard procedure is to determine the expected overvoltages through calculations and to establish the necessary protective level of the arrester by means of insulation coordination studies. Information and instructions for this are found in the IEC publications 60071-1 and 60071-2, and recommendations for the application of surge arresters are made in IEC 60099-5.

It is common to cite the lightning impulse residual voltage also for the double value of the nominal discharge current. The corresponding values are normally between 5% and 15% above the lightning impulse protective level.

In the extra-high-voltage systems the [switching impulse protective level](#) is normally the determining value of an arrester's protective characteristic. In each case it is generally cited, in accordance with IEC-standard 60099-4, for two different [switching current impulse](#) values:

Table 5: Switching current impulses for high-voltage arresters from IEC 60099-4

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

The switching impulse residual voltage is typically between 75% and 90% of the 10 kA lightning current impulse residual voltage, depending each time on the MO resistor in use and the actual switching current impulse value. In the case of a 1 kA switching current impulse, one can take 85% of the 10 kA lightning current impulse residual value as a guideline¹.

Just as with the lightning impulse protective level, the switching impulse protective level is to be selected on the basis that the switching overvoltage on the device to be

¹ Manufacturer-dependent deviations are possible.

protected is not higher than its standard switching impulse withstand voltage¹ divided by the safety factor K_s ($K_s = 1.15$ in the case of non-self-restoring insulation). As a result of the comparatively slow process, voltage increases induced by traveling wave effects or inductive voltage drops, need not be considered. That means that the switching impulse protective level does not need to be lower than the standard switching impulse withstand voltage of the device, divided by a factor of 1.15.

In a few special applications, it is necessary to know the [steep current impulse protective level](#). Thus, it is also typically mentioned in the data sheet of the arrester. The residual voltage of MO resistors is about 5% (in extreme cases 10%) higher for steep current impulses compared with lightning current impulses of the same value. However, the published data of the steep current impulse protective level should be interpreted carefully. Basically the residual voltage during steep current rises (front times in the range of $\leq 1 \mu\text{s}$) is influenced by two different effects which nevertheless always occur together. One of these is the fact that the temporal behavior of the MO material during the transition from the non-conducting to a conducting state presents itself, when seen only externally, as inductive behavior (the residual voltage peak value lies temporally ahead of the peak value of the current, see [Figure 4](#)). Another is that of the inductivity of the geometrical arrangement having an effect of ca. $1 \mu\text{H}$ per meter on the overall height. The latter influence can increase the residual voltage by an additional 5%, or even more. The IEC standard 60099-4 very precisely specifies how these two effects are to be separated, and that both must be included in the specified steep current impulse protective level. Not all manufacturers adhere to these requirements, so if there are any doubts, inquiries should be made.

If, when checking the protective levels of all the cited current impulse stresses, the requirements are fulfilled, then the choice of the electrical characteristic of the arrester is finished at this point. What, however, should be done, if any of these values are too high? For a given type of MO resistor all the residual voltage values, as well as the continuous operating and rated voltage, comprise a fixed ratio. Thus, none of these values can be decreased alone. Instead the whole characteristic would have to be shifted downwards, in order, for example, to obtain a lower switching impulse protective level. This, however, is not allowed, as the continuous operating and rated voltage would also

¹ In this context SIL – the basic switching impulse insulation level – is frequently mentioned. This term, found in the US standards, is, however, not defined in the IEC standards (see explanation of [SIL](#) in the appendix).

automatically become lower by the same percentage, and a stable continuous operation could no longer be guaranteed. In this case there is normally only one single permissible means: MO resistors with larger cross sections must be selected. This can be achieved by choosing a larger diameter or by connecting several resistors in parallel. Generally it is the case that the ratio of the lightning impulse protective level to the rated voltage is smaller, the bigger the MO resistor cross section is. This is easily illustrated using the E - J -characteristic: for the same injected current, the larger cross section results in a lower current density and therefore to lower voltages per millimeter of height ("field strengths"). Therefore, for a given continuous operating and rated voltage, respectively, a larger resistor cross section will result in a lower protective level. The ratio of the residual voltage at a lightning current impulse of 10 kA, to the r.m.s. value of the rated voltage, is between over three in distribution arresters almost down to two for heavy multi-column high-voltage arresters¹. Requirements for low residual voltage values are thus frequently the reason that larger resistors and greater numbers of them, respectively, are used, than would actually be needed for the required energy handling capability (or the line discharge class). Therefore, lower residual voltage values should only be requested when they are absolutely necessary for the application in question.

Selecting the Housing

Dielectric and mechanical requirements are generally taken into account when selecting the housing. The length, the creepage distance, the shed profile, the diameter and the material must all be determined. The arrester characteristics determined by the housing are the [rated short-circuit current](#) I_s , the [specified long-term load](#), SLL, and the [specified short-term load](#), SSL.

The minimal housing length first of all obviously results from the demand that the MO resistor column (the active part) must fit. The length of this column is determined by the electrical data, which was gathered during the selection steps taken up to that point. Normally, however, this is not the dimensioning requirement. Generally further demands cause the housing lengths to be much greater than those of the active parts.

¹ The individual factors are naturally very manufacturer-dependent. However, they are established within this range.

First of all, the [clearance](#), which results from the withstand voltage requirements, must be determined. According to IEC 60099-4 the arrester housing must fulfill the following test requirements:

Table 6: Required withstand voltages of arrester housings from IEC 60099-4

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

Test voltages resulting from these requirements are below those of the other devices of the system, as the following example of the lightning impulse withstand voltage shows: a typical arrester in a 420-kV-system has a lightning impulse protective level of 806 kV (see [Figure 2](#)). Its housing must, therefore, be tested with a lightning impulse voltage of $1.3 \cdot 806 \text{ kV} = 1048 \text{ kV}$, which only comprises 74% of the standard lightning impulse withstand voltage of 1425 kV, as it is normally applied in this system. This is clearly justified because the arrester housing is the best-protected insulation within the system. No higher voltages occur here other than the voltage drop directly across the enclosed MO resistors. At the same time the factors cited in the table already take different atmospheric conditions into account – such as installation at heights of up to 1000 m – as well as the possibility of having arrester currents higher than the nominal discharge current. Nevertheless the same withstand voltage values are unfortunately frequently requested for the arrester housings as those of the rest of the devices, which consequently leads to unnecessarily long housings. The result is then uneconomical and at the same time technically disadvantageous arrester housings¹.

If the site altitude is over 1000 m – which according to the corresponding IEC definition no longer counts as a "normal service condition"² – then greater clearances and

¹ Using longer housings can, for example, result in lower short-circuit strength or a disadvantageous voltage distribution along the arrester axis.

² An explanation will be included later in this section.

housing lengths must be chosen in order to maintain the required withstand voltage values in conditions of lower air density.

A much more frequent reason for longer housings is, however, creepage distance requirements. The shortest possible housing as a result of the length of the active part can normally be achieved only by designing for [pollution levels](#) of "a", "b" or "c"¹, i.e., for [unified specific creepage distances](#) of up to 34.6 mm/kV or [specific creepage distances](#) of up to 20 mm/kV². For central European requirements this is often adequate. Worldwide, however, levels "d" and "e" also play an important role. These lead to unified specific creepage distance requirements of 43.3 mm/kV and 53.7 mm/kV (corresponding to specific creepage distances of 25 mm/kV and 31 mm/kV). In addition, there are locations which make the use of even longer creepage distances necessary, for example those with maritime desert climates, or in some cases, these conditions in combination with industrial pollution. In such extreme conditions it should be noted, however, that there are often other, more appropriate means of improving the operational reliability than increasing the creepage distance. For example, one can select a higher continuous operating and rated voltage (naturally, with associated higher protective levels), or use MO resistors with greater diameters, or housings with greater distances between the active part and the housing wall (to reduce the capacitive coupling between external electrical discharges and the internal active part). At any rate one should keep in mind that "artificial" extensions of the active part (by inserting metal spacers), which are brought about by creepage distance extensions, can also have a negative effect on the rest of the operation behavior, as already mentioned in connection with withstand voltage requirements.

The different shed profiles and some of their characteristics were dealt with in the chapter on "Constructive Design of MO Arresters". A general recommendation for a specific shed profile cannot be given here. When in doubt, in each case, one should be chosen which has proved to be effective in service at the particular site.

Arresters with polymer housing can theoretically make use of a "silicone bonus" if they use silicone rubber sheds. For example, the hydrophobic properties mean that the creepage distance could be reduced to 80% of the value required for a porcelain housing. However, this is not normally done in practice as the hydrophobic properties may

¹ According to the definition in IEC 60815-1

² See the appendix for an explanation of the differences in creepage distance definitions and pollution classes between the old IEC 60815, Ed. 1, 1986 and the current IEC 60815-1, -2, -3, published in 2008.

be lost under certain operating conditions (e.g. constant moisture over a long period) and the housing reverts to insulation characteristics that are comparable to a porcelain housing. Please refer to the explanations in IEC 60815-3.

After the housing parameters have thus far been determined in order to fulfill the electrical requirements, now in the next and last steps, the mechanical criteria follow. They indirectly lead to the selection of the housing material and the housing diameter. Often there is only a vague idea as to the mechanical stress of an arrester in service, and accordingly no requirements are made, or, maybe even worse, ones in which the values are too high. If there is no information available about the actual requirements, the following values can serve as a guideline for the necessary static head loads in high-voltage systems: $F_{\text{stat}} = 350 \text{ N}$ for $U_s = 72.5 \text{ kV}$, $F_{\text{stat}} = 400 \text{ N}$ for $U_s = (123 \dots 420) \text{ kV}$, $F_{\text{stat}} = 600 \text{ N}$ for $U_s = 550 \text{ kV}$ and $F_{\text{stat}} = 800 \text{ N}$ for $U_s = 800 \text{ kV}$. These values represent absolute minimal requirements assuming that the arrester is connected by strain relieving conductor loops and a wind velocity of 34 m/s ($\approx 120 \text{ km/h}$) is not exceeded, which according to IEC 60694 belongs to the "normal service conditions".

Besides the static head loads, which normally cause the arrester few problems, dynamic requirements must also be considered. These can, for example, occur as a result of short-circuit currents on the line, or of gusting winds. In this case arresters with porcelain housing can, because of the brittle properties and statistical behavior of the porcelain, be strained at only up to 40% of its dynamic strength. The specified permissible dynamic head loads should prove, on the other hand, to have at least a 20% safety margin to the actual mean breaking values, ascertained during tests¹. IEC has replaced the static head load with the term [specified long-term load](#) (SLL), and the dynamic head load with [specified short-term load](#) (SSL), and it has introduced the abbreviation MBL for the [mean breaking load](#). The head load values mentioned above can now be expanded upon accordingly in the following table for arresters with porcelain housing:

Table 7: Recommended mechanical characteristics for arresters with porcelain housing

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

¹ Data in accordance with DIN 48113 and IEC 60099-4, Annex M

The ratios look somewhat different for polymer-housed arresters. However, appropriate rules and standards have still not been established because of the many different designs and insufficient real-life experience. At any rate a smaller distance can clearly be adopted between the static and the dynamic loads, since the polymer housing (with the exception of the cast resin housing, which has brittle characteristics similar to those of porcelain, and thus, is considered in exactly the same manner) diverges less in its mechanical characteristics. According to current findings, a static strength utilization of at least 70% of the breaking value (whereby the breaking value is, at the same time, difficult to define and determine for a polymer housing) appears to be unquestionably permissible. Polymer housings, in contrast to porcelain housings, are visibly deflected under the influence of mechanical forces. Generally, this is not a consideration, however, in those cases in which this sort of behavior would cause problems, choosing a mechanically stronger housing must be considered, which will be less strained under the loads occurring here, and thus be less deflected¹.



Fig. 22: Polymer housed arrester for a 550-kV-system during seismic testing on a shaking table

¹ See "[Mechanical loads](#)" in the appendix for more information.

For polymer-housed arresters in distribution systems a dynamic strength (SSL) of 250 N can be considered sufficient, resulting in a static strength (SLL) of 175 N.

While the values cited in Table 7 indicate relatively minimal demands on the housing strength, these can escalate enormously when taking seismic requirements into account. Such requirements go beyond the "normal operation conditions", and the associated demands must be explicitly described in an enquiry. There are various standardized calculation and test procedures which determine the behavior of an arrester under such conditions. Typically a completely assembled arrester is subjected to an earthquake test on a shaking table, on which at least two and preferably three axes are accelerated at the same time (**Figure 22**). The excitation may be carried out sinusoidal – temporary or transient – or occur at a spectrum of different frequencies and amplitudes, in order, as nearly as possible, to simulate a real earthquake ("time-history-test"). Extreme requirements can in many cases more easily be fulfilled with the use of polymer housings, especially with the "tube design", than with porcelain housings.

Taking seismic requirements into consideration is a common need for only a few locations worldwide. However, out of the previous list of mechanical characteristics, the short-circuit withstand capability must be considered in every case. It characterizes the failure mode of an arrester after the occurrence of an operational overload of the MO resistors. On very rare occasions an overload may occur, for example in a distribution system as a result of a [nearby direct lightning strike](#) or – even less frequently – because of a power-frequency voltage transfer in a high-voltage system from one system with a higher to another with a lower voltage, caused by a damaged conductor or line galloping. After overloading, an arc develops inside of the arrester housing, through which the site-specific power-frequency short-circuit current flows. In an arrester with an enclosed gas volume, pressure then increases instantaneously within the inner-housing. Pressure relief devices, however, prevent the housing from exploding. Accordingly, the relevant test standards (IEC 60099-1, IEC 60099-4, IEEE C62.11) used to refer to the "pressure relief behavior" and to "pressure relief tests", and partly continue to do so to this day. As the new polymer insulated arresters in part no longer contain enclosed gas volumes in their housing, it makes sense to refer more generally to "short-circuit behavior", and accordingly the associated tests are now called "[short-circuit tests](#)" in IEC 60099-4. No defined pressure builds up in this type of housing to activate a pressure relief device – instead, the resulting arc seeks a path through the housing wall to an arbitrary point or points that have been specially provided. The goal, however, always remains the same: in the case of an arrester overloading, according to the test requirements, the housing must either remain intact, or if it breaks, the housing fragments and the ejected parts

must fall to the ground within a circumference around the arrester, whose radius is about the same as the height of the arrester (this means a permissible angle of the parts of approximately 45 °). Housing breakage that fulfills these requirements is expressly permissible. Under no circumstances, however, is a violent shattering of the housing allowed, whereby "violent shattering" is defined as occurring when fragments fall outside the area around the arrester in which the parts are required to remain¹. Only parts up to a maximum 60 g in weight may be found outside the area². The chance of a housing breakage must be considered when building a substation. Because of this risk it is generally advisable, for example, to avoid using an arrester as a post insulator for a conductor or a busbar. If this, however, is desired, polymer-housed arresters with the "tube design" should be used, whereby it should be noted that the required behavior cannot automatically be found in all designs.

The maximum short-circuit current, flowing for a period of 200 ms, is the [rated short-circuit \(withstand\) current](#) I_s given in amperes. The following table presents the standard rated short-circuit (withstand) currents and the further testing requirements:

Table 8: Currents in the short-circuit test (from IEC 60099-4)

Rated short-circuit current (duration 200 ms) / A	Reduced short-circuit currents (duration 200 ms) / A		Low short-circuit current (duration 1 s) / A
80 000	50 000	25 000	600 ± 200
63 000 ³	25 000	12 000	
50 000	25 000	12 000	
40 000	25 000	12 000	
31 500	12 000	6 000	
20 000	12 000	6 000	
16 000	6 000	3 000	
10 000	6 000	3 000	
5 000	3 000	1 500	

¹ Unless they have witnessed a failed short-circuit test, people are inclined to use the word "explosion" for an arrester that breaks apart when not even under pressure. In fact, a real, unsuccessful pressure relief can hurl large pieces of the arrester tens of meters away.

² After an otherwise successful short-circuit test, tiny pieces of the arrester are often found outside the area, propelled there purely by the pressure wave caused by the arc.

³ Tests for $I_s = 63\,000\text{ A}$ are frequently carried out with 65 kA in order to meet the testing requirements of the IEEE standard, which stipulates current values in 5-kA steps for currents $\geq 40\text{ kA}$.

The rated short-circuit (withstand) current selected when the arrester is chosen should at least comply with the maximum short-circuit current expected at the location of the arrester. The testing standard requires that the test is carried out with the full rated short-circuit (withstand) current such that the current is overlaid with a decaying DC component, to reach the peak value of 2.5 times the root-mean-square value (where $I_s = 80\,000\text{ A}$, this means that a peak value of 200 kA must be reached in the test!). This reproduces the worst case of a short-circuit close to the generator. The table continues to list reduced short-circuit currents of around 50% and 25% of the rated short-circuit (withstand) current that must also be tested. The reason is that it has occasionally been observed in practice that the arrester housing shatters at short-circuit currents below the specified maximum because the pressure relief devices were only optimized for the extreme case and reacted too sluggishly at lower currents. Finally, the test must also be carried out with a standard "low short-circuit current" of $600\text{ A} \pm 200\text{ A}$. This current flows for a duration of one second, and within this time period the pressure relief devices (if existing in the design) must have opened. This part of the test is carried out to prove that the pressure relief devices of the arrester can also open under very low fault current stress. For polymer-housed arresters it also demonstrates the arrester's resistance to fire.

For the high currents, short-circuit withstand capability is tested on the longest unit of a type. For arresters with porcelain housing it is influenced most of all by the following parameters:

- Housing diameter: greater diameters bring about higher strength
- Housing length: the greater the length, the lower the strength at a given diameter
- Wall thickness: strength increases with increasing wall thickness
- Housing material: the porcelain quality "C 120" results in greater strength than quality "C 110"

For the first two parameters the same contexts generally apply for polymer-housed arresters. There are, however, other design factors that have an effect, for example whether it is an arrester with an enclosed gas volume ("tube design") or not, and if not, whether it is a "cage design" or "wrapped design", and which particular version. This will not be discussed in further detail here. **Figures 23 to 25** show the results of successfully completed short-circuit tests with the rated short-circuit (withstand) current, on two polymer-housed arrester types and one porcelain housed arrester.



Fig. 23: Polymer-housed arrester ("tube-design") after a short-circuit test at rated current (65 kA, 200 ms). The housing is ripped but in mechanically sound condition. Details of the test setup can well be seen. For further information see [short-circuit tests](#) in the appendix.

At this point the selection of an arrester is complete. Altogether the mechanical requirements – that is, the required head loads, the seismic demands and the short-circuit withstand capability – determine the appropriate combination of housing material and type, diameter and length. At the same time the length of a porcelain housing is restricted to a size of about two meters for technical and manufacturing reasons. For polymer-housed arresters – at least for certain designs – greater lengths are possible and common. If the required total length of an arrester is greater than is possible to enclose in a single housing, then the arrester is made up of several units. It is, however, not only a question of cost – several units means that multiple flanges, sealing systems, pressure relief devices, etc. exist – it is also advantageous to use single unit arresters if they are operated in a heavily polluted environment¹. At present this is possible for arresters with porcelain housings with a highest system voltage of up to 245 kV and for certain designs of polymer-housed arresters at a level of up to 300 kV.

¹ With multi-unit arresters under certain conditions, it is theoretically possible for pollution-related currents flowing on the housing surface at the intermediate flanges to commutate into the active parts of the adjacent units and heat up the active parts there.



Fig. 24: Polymer-housed arrester ("tube design") after a test at rated short-circuit current (80 kA, 200 ms). The housing has remained completely intact.



Fig. 25: Porcelain-housed arrester after a test at rated short-circuit current (63 kA, 200 ms). Apart from a few broken sheds, the housing has remained intact.

Service Conditions

"Normal service conditions" have been mentioned a few times already. Normally all the characteristic values are only determined for normal service conditions by the manufacturer. Thus, during the selection of an arrester, it is necessary to check whether these conditions apply to the planned installation. The following is a list of normal service conditions¹ found in standard IEC 60099-4, 5.4.1:

- Ambient air temperature within the range of -40°C to $+40^{\circ}\text{C}$
- Solar radiation 1.1 kW/m^2
- Altitude not exceeding 1000 m above sea level
- Frequency of the a.c. power supply not less than 48 Hz and not exceeding 62 Hz

¹ Examples for "abnormal service conditions" are included in Annex A of IEC 60099-4. Also Annex G continues to provide information on enquiries and tenders.

- Power-frequency voltage applied continuously between the terminals of the arrester not exceeding the arrester's continuous operating voltage
- Wind velocity ≤ 34 m/s
- Vertical mounting of the arrester

Examples

The description of the configuration and selection procedure is now concluded, and some explanatory numerical examples¹ are provided below. To begin with, they refer to the most common application of arresters between phases and the earth ("phase arresters"), and are to be understood as standard layouts, as they would have been intended by a manufacturer if no further requirements and information, respectively, are submitted with an arrester enquiry other than that of the system voltage and the type of neutral earthing of the system. At the same time, this represents the minimally required information, without which an arrester cannot be reasonably laid out. Of course, the resulting arrester may only fulfill the absolute minimum requirements of the system. The characteristic values determined on the basis of so little input data should be carefully checked so that none of the actual system requirements are overlooked. The more precisely the information and requirements are specified, the more likely the resulting arrester will fulfill all the demands of the application in question. In special cases a system or insulation coordination study can prove the effectiveness of an arrester layout and the associated achievable protection of the equipment against lightning and switching overvoltage.

In the end the electrical configuration of arresters to protect the neutral point of the transformer ("neutral point arresters") is briefly described.

The numerical examples represent functioning minimal configurations. However, they are not necessarily typical or common layouts. Instead for good reasons, normally more safety would be provided for. By choosing the continuous operating and the rated voltage higher than is minimally required, it is possible to increase the operational reliability considerably, while in most cases the corresponding increase in the protective level can be tolerated. Some national versions of the application guide IEC 60099-5 – for instance the German – have typical arrester configurations included in their Informative Annex B, from which the most common values for continuous operating and rated voltages and the protective levels for the individual system voltage levels can be obtained.

¹ The resulting characteristic values are to be regarded as reference values; details are naturally manufacturer-specific.

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

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

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

- $U_s = 72.5$ kV
- LIWV = 325 kV
- earth fault factor $k = 1.4$
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 10$ kA
- required line discharge class: 1
- pollution level: b ("light")
- maximum short-circuit current: 20 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = 1.05 \cdot U_s / \sqrt{3} = 1.05 \cdot 72.5 / \sqrt{3}$ kV = 44 kV
- $U_{rl, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 44$ kV = 55 kV
- $U_{r2, \min} = 1.4 \cdot (U_s / \sqrt{3}) / k_{\text{tov}, 10 \text{ s}} = 1.4 \cdot (72.5 / \sqrt{3}) / 1.075^* \text{ kV} = 55 \text{ kV}$
($k_{\text{tov}, 10 \text{ s}}$ from [Figure 20](#))

Establishing the actual continuous operating and rated voltage:

- $U_r = U_{rl, \min}$ rounded up to the next value divisible by 3 = 57 kV

Normally an arrester with a rated voltage of at least 60 kV is used in this system. This leads to a more stable layout, and nevertheless offers a sufficiently low protective level.

- $U_r = 60$ kV
- $U_c = U_r / 1.25^* = 60 \text{ kV} / 1.25^* = 48$ kV

Selecting an MO resistor suitable for $I_n = 10$ kA and LD-class 1

- MO diameter: 40* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.65^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 1.)

The resulting protective characteristics* :

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 159 kV
- switching impulse protective level ($\hat{u}_{0.5 \text{ kA}, 30/60 \mu\text{s}}$): 122 kV
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/<20 \mu\text{s}}$): 169 kV

Checking the protective values:

- $LIWV/\hat{u}_{10\text{ kA}, 8/20\text{ }\mu\text{s}} = 325\text{ kV}/159\text{ kV} = 2.04 \rightarrow \text{definitely sufficient}$

Height of the MO resistor column:

- $h_{\text{MO}} = 400^* \text{ mm}$

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 159\text{ kV} = 207\text{ kV}$
- power-frequency withstand voltage 1 min, wet =
 $1.06/\sqrt{2} \cdot \text{switching impulse protective level} = 1.06/\sqrt{2} \cdot 122\text{ kV} = 92\text{ kV}$
- creepage distance: $16\text{ mm/kV} \cdot 72.5\text{ kV}$ ($27.7\text{ mm/kV} \cdot 41.9\text{ kV}$) = 1160 mm
- permissible head load static (SLL): 350 N
- permissible head load dynamic (SSL): 500 N
- rated short-circuit current (rated short-circuit (withstand) current I_s): 20 kA
- possible length of the active part: 400 mm
- number of units: 1
- grading ring: no

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

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

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

- $U_s = 123 \text{ kV}$
- $\text{LIWV} = 550 \text{ kV}$
- operation under earth fault conditions for $> 30 \text{ min.}$
- required nominal discharge current $I_n = 10 \text{ kA}$
- required line discharge class: 2
- pollution level: b ("light")
- maximum short-circuit current: 40 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = U_s = 123 \text{ kV}$
- $U_{r, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 123 \text{ kV} = 154 \text{ kV}$
(The rated voltage, however, has no technical significance in a resonant earthed system.)

Establishing the actual continuous operating and rated voltage:

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

Selecting an MO resistor suitable for $I_n = 10 \text{ kA}$ and LD-class 2

- MO diameter: 60^* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.3^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 2.)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 359 kV^2

¹ Power-frequency voltage values are rounded down to whole numbers.

² Residual voltage values are mathematically rounded to whole numbers.

- switching impulse protective level ($\hat{u}_{0,5 \text{ kA}, 30/60 \mu\text{s}}$): 287 kV
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/<20 \mu\text{s}}$): 381 kV (without influence of geometry)

Checking the protective values:

- $\text{LIWV}/\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}} = 550 \text{ kV}/359 \text{ kV} = 1.53 \rightarrow \text{generally sufficient}$

Height of the MO resistor column:

- $h_{\text{MO}} = 1000^* \text{ mm}$

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 359 \text{ kV} = 467 \text{ kV}$
- power-frequency withstand voltage 1 min, wet =
 $1.06/\sqrt{2} \cdot \text{switching impulse protective level} = 1.06/\sqrt{2} \cdot 287 \text{ kV} = 215 \text{ kV}$
- creepage distance: $16 \text{ mm/kV} \cdot 123 \text{ kV}$ ($27,7 \text{ mm/kV} \cdot 71 \text{ kV}$) $\approx 1970 \text{ mm}$
- permissible head load static (SLL): 400 N
- permissible head load dynamic (SSL): 1000 N
- rated short-circuit current (rated short-circuit (withstand) current I_s): 40 kA
- possible length of the active part: 1000 mm
- number of units: 1
- grading ring: no

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

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

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

- $U_s = 245 \text{ kV}$
- LIWV = 950 kV
- earth fault factor $k = 1.4$
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 10 \text{ kA}$
- required line discharge class: 3
- pollution level: b ("light")
- maximum short-circuit current: 50 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = 1.05 \cdot U_s / \sqrt{3} = 1.05 \cdot 245 / \sqrt{3} \text{ kV} = 149 \text{ kV}$
- $U_{rl, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 149 \text{ kV} = 187 \text{ kV}$
- $U_{r2, \min} = 1.4 \cdot (U_s / \sqrt{3}) / k_{\text{tov}, 10 \text{ s}} = 1.4 \cdot (245 / \sqrt{3}) / 1.075^* \text{ kV} = 185 \text{ kV}$
($k_{\text{tov}, 10 \text{ s}}$ from [Figure 20](#))

Establishing the actual continuous operating and rated voltage:

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

Selecting an MO resistor suitable for $I_n = 10 \text{ kA}$ and LD-class 3

- MO diameter: 60* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.4^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 3. Compare with Example 2!)

The resulting protective characteristics* :

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 475 kV
- switching impulse protective level ($\hat{u}_{1 \text{ kA}, 30/60 \mu\text{s}}$): 394 kV
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/<20 \mu\text{s}}$): 504 kV (without influence of geometry)

Checking the protective values:

- $\text{LIWV}/\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}} = 950 \text{ kV}/475 \text{ kV} = 2.0 \rightarrow$ definitely sufficient

Height of the MO resistor column:

- $h_{\text{MO}} = 1300^* \text{ mm}$

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 475 \text{ kV} = 618 \text{ kV}$
- power-frequency withstand voltage 1 min, wet =
 $1.06/\sqrt{2} \cdot \text{switching impulse protective level} = 1.06/\sqrt{2} \cdot 394 \text{ kV} = 295 \text{ kV}$
- creepage distance: $16 \text{ mm/kV} \cdot 245 \text{ kV}$ ($27.7 \text{ mm/kV} \cdot 141.5 \text{ kV}$) = 3920 mm
- permissible head load static (SLL): 400 N
- permissible head load dynamic (SSL): 1000 N
- rated short-circuit current (rated short-circuit (withstand) current I_s): 50 kA
- possible length of the active part: 1300 mm
- number of units: 1*
- grading ring* : no (borderline case)

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

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

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

- $U_s = 420 \text{ kV}$
- $\text{LIWV} = 1425 \text{ kV}$
- earth fault factor $k = 1.4$
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 10 \text{ kA}$
- required line discharge class: 3
- pollution level: d ("heavy")
- maximum short-circuit current: 50 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = 1.05 \cdot U_s / \sqrt{3} = 1.05 \cdot 420 / \sqrt{3} \text{ kV} = 255 \text{ kV}$
- $U_{rl, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 255 \text{ kV} = 319 \text{ kV}$
- $U_{r2, \min} = 1.4 \cdot (U_s / \sqrt{3}) / k_{\text{tov}, 10 \text{ s}} = 1.4 \cdot (420 / \sqrt{3}) / 1.075^* \text{ kV} = 316 \text{ kV}$
($k_{\text{tov}, 10 \text{ s}}$ from [Figure 20](#))

Establishing the actual continuous operating and rated voltage:

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

Selecting an MO resistor suitable for $I_n = 10 \text{ kA}$ and LD-class 3

- MO diameter: 60* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.4^*$ (This factor is characteristic for the MO resistor used when configuring it for the line discharge class 3. Compare with example 2!)

The resulting protective characteristics* :

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 806 kV
- switching impulse protective level ($\hat{u}_{1 \text{ kA}, 30/60 \mu\text{s}}$): 669 kV
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/<20 \mu\text{s}}$): 854 kV (without influence of geometry)

Checking the protective values:

- $\text{LIWV}/\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}} = 1425 \text{ kV}/806 \text{ kV} = 1.77 \rightarrow \text{definitely sufficient}$

Height of the MO resistor column:

- $h_{\text{MO}} = 2200^* \text{ mm}$

Selecting a Housing

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 806 \text{ kV} = 1048 \text{ kV}$
- switching impulse withstand voltage =
 $1.25 \cdot \text{switching impulse protective level} = 1.25 \cdot 669 \text{ kV} = 836 \text{ kV}$
- creepage distance: $25 \text{ mm/kV} \cdot 420 \text{ kV}$ ($43.3 \text{ mm/kV} \cdot 242.5 \text{ kV}$) = 10500 mm
- permissible head load static (SLL): 400 N
- permissible head load dynamic (SSL): 1000 N
- rated short-circuit current (rated short-circuit (withstand) current I_s): 50 kA
- possible length of the active part : 2200 mm ($2 \cdot 1100 \text{ mm}$)^{*}
- number of units: 2^{*}
- grading ring: yes

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

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

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

- $U_s = 550 \text{ kV}$
- LIWV = 1550 kV
- earth fault factor $k = 1.4$
- maximum duration of temporary overvoltage: 10 s
- required nominal discharge current $I_n = 20 \text{ kA}$
- required line discharge class: 5
- pollution level: d ("heavy")
- maximum short-circuit current: 50 kA

Special information and requirements for the particular case:

- $U_s = 525 \text{ kV}$
- switching impulse protective level ($\hat{u}_2 \text{ kA}, 30/60 \mu\text{s}$): $\leq 760 \text{ kV}$ ¹
- energy handling capability: $\geq 5 \text{ MJ}$
- creepage distance: 25 mm/kV (of U_{ph-ph})
- seismic withstand capability: ground acceleration $0.5 \cdot g$ according to US standard IEEE 693 (\rightarrow arrester base acceleration $1 \cdot g$) ²

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = 1.05 \cdot U_s / \sqrt{3} = 1.05 \cdot 525 / \sqrt{3} \text{ kV} = 318 \text{ kV}$
- $U_{rl, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 318 \text{ kV} = 398 \text{ kV}$
- $U_{r2, \min} = 1.4 \cdot (U_s / \sqrt{3}) / k_{tov, 10 \text{ s}} = 1.4 \cdot (525 / \sqrt{3}) / 1.075^* \text{ kV} = 395 \text{ kV}$
($k_{tov, 10 \text{ s}}$ from [Figure 20](#))

¹ Demands for low switching impulse protective levels are typical of extra-high-voltage systems, see chapter "Configuring MO Arresters".

² According to IEEE 693 an arrester's seismic performance is preferably verified by a multi-axes "time history test" on a shaking table. If the arrester is tested without a pedestal (which, for practical reasons, is the usual case) the acceleration at the arrester base must be double the value of the required ground acceleration, assuming an amplification factor of two for a typical pedestal. Furthermore, according to IEEE 693, a mechanical stress of not more than 50 % of the arrester's mechanical breaking strength is allowed to occur during the test. These are the reasons that an extremely high mechanical strength is necessary to fulfill the $0.5 \cdot g$ ground acceleration requirement.

Establishing the actual continuous operating and rated voltage:

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

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

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

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

The resulting protective characteristics* :

- lightning impulse protective level ($\hat{u}_{20 \text{ kA}, 8/20 \mu\text{s}}$): 926 kV
- switching impulse protective level ($\hat{u}_{2 \text{ kA}, 30/60 \mu\text{s}}$): 760 kV
- steep current impulse protective level ($\hat{u}_{20 \text{ kA}, 1/<20 \mu\text{s}}$): 982 kV (without influence of geometry)
- energy handling capability (thermal): 18 kJ/kV of $U_r \rightarrow 7.2$ MJ total

Checking the protective values:

- $LIWV/\hat{u}_{20 \text{ kA}, 8/20 \mu\text{s}} = 1550 \text{ kV}/926 \text{ kV} = 1.67 \rightarrow$ definitely sufficient
- switching impulse protective level requirement fulfilled
- energy handling capability requirement fulfilled

Height of the MO resistor column(s):

- $h_{MO} = 2700^*$ mm

Selecting a Housing (composite hollow core insulator* - "tube design" – in order to fulfill the seismic requirements)

Minimal requirements:

- lightning impulse withstand voltage =
1.3 · lightning impulse protective level = 1.3 · 926 kV = 1204 kV
- switching impulse withstand voltage =
1.25 · switching impulse protective level = 1.25 · 760 kV = 950 kV
- creepage distance: 25 mm/kV · 525 kV (43.3 mm/kV · 303.1 kV) = 13125 mm
- permissible head load dynamic (SSL): 16400 N (due to seismic requirements!)
- permissible head load static (SLL): 11500 N (= 70 % of the dynamic value)
- rated short-circuit current (rated short-circuit (withstand) current I_s): 50 kA
- possible length of the active part : 2700 mm (2 · 1350 mm)*

- number of units: 2* (in porcelain 3* units would be necessary)
- grading ring: yes

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

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

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

- $U_s = 24 \text{ kV}$
- LIWV = 125 kV
- operation under earth fault conditions for > 30 min.
- required nominal discharge current $I_n = 10 \text{ kA}$
- pollution level: b ("light")
- maximum short-circuit current: 20 kA

Determining the minimally required continuous operating and rated voltage

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

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

Establishing the actual continuous operating and rated voltage:

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

Selecting an MO resistor suitable for $I_n = 10 \text{ kA}$

- MO diameter: 40^* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.65^*$ (This factor is characteristic for the MO resistor used.)

The resulting protective characteristics* :

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 80 kV
(→ in accordance with the German application guide DIN EN 60099-5/VDE 0675, Part 5: required lightning impulse protective level $\leq 80 \text{ kV}$)
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/\leq 20 \mu\text{s}}$): 85 kV (without influence of geometry)

Checking the protective values:

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

Height of the MO resistor column:

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

Selecting a Housing (Polymeric Type)

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 80 \text{ kV} = 104 \text{ kV}$
- power-frequency withstand voltage 1 min, wet =
 $0.88 / \sqrt{2} \cdot \text{lightning impulse protective level} = 0.88 / \sqrt{2} \cdot 80 \text{ kV} = 50 \text{ kV}$
- creepage distance: $16 \text{ mm/kV} \cdot 24 \text{ kV}$ ($27.7 \text{ mm/kV} \cdot 13.9 \text{ kV}$) $\approx 385 \text{ mm}$
- permissible head load static (SLL): 175 N
- permissible head load dynamic (SSL): 250 N
- short circuit withstand capability (rated short-circuit (withstand) current I_s): 20 kA
- possible length of the active part: 200 mm
- number of units: 1 (in medium voltage this is generally the case)
- grading ring: for medium voltage arresters this is generally not necessary

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

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

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

- $U_s = 24 \text{ kV}$
- $LIWV = 125 \text{ kV}$
- earth fault factor $k = 1.4$
- required nominal discharge current $I_n = 10 \text{ kA}$
- pollution level: b ("light")
- maximum short-circuit current: 20 kA

Determining the minimally required continuous operating and rated voltage

- $U_{c, \min} = 1.05 \cdot U_s / \sqrt{3} = 1.05 \cdot 24 / \sqrt{3} \text{ kV} = 14.6 \text{ kV}$
- $U_{rl, \min} = 1.25^* \cdot U_{c, \min} = 1.25^* \cdot 14.6 \text{ kV} = 18.3 \text{ kV}$
- $U_{r2, \min} = 1.4 \cdot (U_s / \sqrt{3}) / k_{\text{tov}, 10 \text{ s}} = 1.4 \cdot (24 / \sqrt{3}) / 1.0^* \text{ kV} = 19.4 \text{ kV}$
($k_{\text{tov}, 10 \text{ s}}$ is different from that of [Figure 20](#) for the distribution arrester under consideration!)

Establishing the actual continuous operating and rated voltage:

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

Selecting an MO resistor suitable for $I_n = 10 \text{ kA}$

- MO diameter: 40* mm
- $\hat{u}_{10 \text{ kA}} / U_r = 2.65^*$ (This factor is characteristic for the MO resistor used.)

The resulting protective characteristics*:

- lightning impulse protective level ($\hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}}$): 56 kV (Compare with Example 6!)
- steep current impulse protective level ($\hat{u}_{10 \text{ kA}, 1/<20 \mu\text{s}}$): 59 kV (without influence of geometry)

Checking the protective values:

- $LIWV / \hat{u}_{10 \text{ kA}, 8/20 \mu\text{s}} = 125 \text{ kV} / 56 \text{ kV} = 2.15 \rightarrow \text{definitely sufficient}$

Height of the MO resistor column:

- $h_{\text{MO}} = 135^* \text{ mm}$

Selecting a Housing (Polymeric Type)

Minimal requirements:

- lightning impulse withstand voltage =
 $1.3 \cdot \text{lightning impulse protective level} = 1.3 \cdot 56 \text{ kV} = 73 \text{ kV}$
- power-frequency withstand voltage 1 min, wet =
 $0.88 / \sqrt{2} \cdot \text{lightning impulse protective level} = 0.88 / \sqrt{2} \cdot 56 \text{ kV} = 35 \text{ kV}$
- creepage distance: $16 \text{ mm/kV} \cdot 24 \text{ kV}$ ($27.7 \text{ mm/kV} \cdot 13.9 \text{ kV}$) $\approx 385 \text{ mm}$
- permissible head load static (SLL): 175 N
- permissible head load dynamic (SSL): 250 N
- short circuit withstand capability (rated short-circuit (withstand) current I_s): 20 kA
- possible length of the active part: 135 mm
- number of units: 1 (in medium voltage this is generally the case)
- grading ring: for medium voltage arresters this is generally not necessary

Arresters to protect transformer neutral points

Arresters to protect transformer neutral points from overvoltages, or "neutral point arresters" for short, are the most common special application of arresters. For example, the IEC 60099-5 application guide recommends the use of an arrester to protect each unearthed neutral point from lightning and switching overvoltage if the neutral point is accessible through a bushing. Following the very detailed explanation of the configuration of phase arresters, the particular features of neutral point arresters are only covered briefly here. The following statements apply in all cases:

- The line discharge class of neutral point arresters should at least be the same as the line discharge class of the associated phase arresters.
- The 1-kA residual voltage level can be used as the protective level because higher currents do not occur.
- The safety margin between the lightning impulse withstand voltage (LIWV) of the transformer neutral point and the arrester protective level can be smaller than for the phase arresters because the voltage increases are not fast enough for traveling wave processes to become a concern.
- For a fully insulated transformer neutral point, IEC 60099-5 recommends choosing a rated voltage for neutral point arresters that is equal to about 60% that of the related phase arresters $U_{r, \text{Np-A}} \approx 0.6 \cdot U_{r, \text{Ph-A}}$
- However, to provide relief for the phase arresters, neutral point arresters and phase arresters can be coordinated so that in the case of intermittent earth faults, for example, the neutral point arresters act more quickly than the phase arresters, thus relieving the phase arresters. In this case the recommendation is $U_{r, \text{Np-A}} \approx 0.45 \cdot U_{r, \text{Ph-A}}$, in other words the rated voltage of the neutral point arresters is only about 45% that of the phase arresters. This approach is frequently used in Germany. Of course, this means that the neutral point arresters have a higher risk of overload, and indeed, neutral point arresters are the only high-voltage arresters with a failure rate significantly higher than zero (deliberately!). For this reason, arresters configured in this way must be contained in a housing with extremely high short-circuit withstand capability. For example, arresters with polymer housing offer maximum safety in this respect, preferably using the "tube design".

Each national version of the IEC 60099-5 application guide for surge arresters usually contains tables in Annex B showing the arrester characteristics, which are common in that country, for phase arresters as well as neutral point arresters. Please refer to these tables for typical neutral point arresters.

Standards

The selection below describes the current state of the most important IEC (and some other) standards on arresters and the associated topics.

Since January 1997, the IEC publications have been numbered differently, in order to achieve correspondence to European and international standards. This is done by adding the number 60000 to the old number. The same holds true for the publications published before 1997, even if they currently still have the old number.

The US standards and application guides on arresters and insulation coordination have also been included because of their importance for the American and other national markets.

a) IEC arrester standards

IEC 60099-1, Edition 3.1, 1999-12

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

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

Note: This standard is no longer updated and may be withdrawn in the near future.

IEC 60099-4, Edition 2.2, 2009-05

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

IEC 60099-5, Edition 1.1, 2000-03

Surge arresters – Part 5: Selection and application recommendations

Note: A completely new edition of IEC 60099-5 (Edition 2) is currently being drafted by IEC TC37 MT10 ("Maintenance Team 10") and is undergoing approval. The current version is IEC document 37/371/CDV. After introduction of several necessary changes the FDIS will be published by end of 2011.

IEC 60099-6, First Edition, 2002-08

Surge arresters – Part 6: Surge arresters containing both series and parallel gapped structures – Rated 52 kV and less

Note: This standard was not accepted by CENELEC, and therefore no European Standard (EN) version exists. The standard covers a very specific design of internally gapped MO arresters, which are applied mainly in the American market.

IEC 60099-8 Ed. 1.0, 2011-01

Surge arresters - Part 8: Metal-oxide surge arresters with external series gap (EGLA) for overhead transmission and distribution lines of a.c. systems above 1 kV

b) IEC standards on insulation coordination

IEC 60071-1, Eighth Edition, 2006-01

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

IEC 60071-2, Third Edition, 1996-12

Insulation co-ordination – Part 2: Application guide

IEC TR 60071-4, First Edition: 2004-06

Insulation co-ordination – Part 4: Computational guide to insulation co-ordination & modelling of electrical networks

IEC TS 60071-5, First Edition, 2002-06

Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations

c) Other international and national standards, also relevant for arresters

IEC 60060-1, Ed. 3.0, 2010-09

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

IEC 60507, Second edition 1991-04

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

IEC 60672-3, Second Edition, 1997-10

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

IEC 60694, Second Edition, 1996-05

Common specifications for high-voltage switchgear and control standards

IEC/TS 60815-1, Ed. 1.0, 2008-10

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles

IEC/TS 60815-2 Ed. 1.0, 2008-10

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 2: Ceramic and glass insulators for a.c. systems

IEC/TS 60815-3 Ed. 1.0, 2008-10

Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 3: Polymer insulators for a.c. systems

DIN 48 113, September 1973

Stützisolatoren für Schaltgeräte und Schaltanlagen für Spannungen über 1 kV – Zuordnung der Begriffe für Biegefestigkeit

HD 637 S1:1999

Power installations exceeding AC 1 kV

IEC 61936-1, Ed. 2.0, 2010-08

Power installations exceeding 1 kV a.c. – Part 1: Common rules

IEC 62073, First Edition, 2003-06

Guidance on the measurement of wettability of insulator surfaces

d) American arrester standards

IEEE C62.11-2005 (Revision of IEEE C62.11-1999)

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

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

IEEE Std. C62.22-2009 (Revision of IEEE C62.22-1997)

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

Literature

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

Cigré Technical Brochure 60

Metal Oxide Arresters in AC Systems

April 1991

Cigré Technical Brochure xxx (no number yet)

Evaluation of stresses of Surge Arresters and appropriate test procedures

Expected: 2012 (WG A3.17)

Cigré Technical Brochure 455

Aspects for the Application of Composite Insulators to High Voltage (≥ 72 kV) Apparatus

April 2011 (WG A3.21)

Cigré Working Group 33.06

Metal oxide surge arresters in AC systems

Part 1: General properties of the metal oxide surge arrester

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

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

ELECTRA 128, pp. 99-125

Cigré Working Group 33.06

Metal oxide surge arresters in AC systems

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

ELECTRA 130, pp. 78-115

Cigré Working Group 33.06

Metal oxide surge arresters in AC systems

Part 5: Protection performance of metal oxide surge arresters

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

ELECTRA 133, pp. 133-165

Göhler, Schubert, Weck, Hinrichsen, Tuzek, Clemens, Appel

Special Requirements on Surge Arrester Design for UHV A.C. Systems above 800 kV
System Voltage

Cigré Session 2010, Paris, Report A3-104-2010

Heinrich, Hinrichsen

Diagnostics and Monitoring of Metal-Oxide Surge Arresters in High-Voltage Networks - Comparison of Existing and Newly Developed Procedures

IEEE Transactions on Power Delivery, Vol. 16, No. 1, January 2001, pp. 138-143

Hinrichsen, Göhler, Lipken, Breilmann

Economical overvoltage protection by metal-oxide surge arresters integrated in 420-kV centre-break disconnectors - Substation integration, design and test experience

CIGRÉ Session 2000, Paris, Report 33-104

Hinrichsen

Latest Designs and Service Experience with Station-Class Polymer Housed Surge Arresters

World Conference on Insulators, Arresters & Bushings, Marbella (Málaga), Spain,
November 16-19, 2003, Proceedings pp. 85-96

Hinrichsen

Latest Test Requirements and Emerging Standards for Transmission Line Arresters

World Conference on Insulators, Arresters & Bushings, Hong Kong, November 27-30,
2005

Hinrichsen

Overview of Recent Technological Developments for HV Line and Station Arresters
& Future Tendencies

World Conference on Insulators, Arresters & Bushings, Rio de Janeiro, May 14-16,
2007

Hinrichsen, Reinhard, Richter (on behalf of Cigré WG A3.17)

Energy Handling Capability of High-Voltage Metal-Oxide Surge Arresters - Part 1: A
Critical Review of the Standards

Cigré SC A3 Technical Colloquium, Rio de Janeiro, September 12/13, 2007

Hinrichsen

Testing Requirements and Actual IEC Work on Distribution and Transmission Line Arresters

Cigré Colloquium "Application of Line surge Arresters in Power Distribution and Transmission Systems", Cavtat/Croatia, May 26 to 29, 2008

Hinrichsen, Göhler, Clemens, Steinmetz, Riffon

External Grading Systems for UHV Metal-Oxide Surge Arresters - A New Approach to Numerical Simulation and Dielectric Testing

Cigré Session 2008, Paris, Report A3-205

Hinrichsen, Tuczek, Reinhard

Recent Experimental Findings on the Energy Handling Capability of Metal-Oxide Varistors for High-Voltage Applications

World Congress on Insulators, Arresters and Bushings, Crete, May 10-13, 2009

Hinrichsen, Möhring, Wietoska, Haupt, Bockenheimer, Heinemann, Berger, Gottschalk, Kurda, Mikli, Schmuck, Seifert

Resistance to Vapor Permeation of Factory New and of Mechanically Stressed Composite Hollow Insulators

Cigré Session 2010, Paris, Report A3-304-2010

Reinhard, Hinrichsen, Richter, Greuter (on behalf of Cigré WG A3.17)

Energy Handling Capability of High-Voltage Metal-Oxide Surge Arresters - Part 2: Results of a Research Test Program

Cigré Session 2008, Paris, Report A3-309

Richter, Schmidt, Kannus, Lahti, Hinrichsen, Neumann, Petrusch, Steinfeld

Long Term Performance of Polymer Housed MO-Surge Arresters

CIGRÉ Session 2004, Paris, Report A3-110

Sakshaug, Kresge, Miske

A new Concept in Station Arrester Design

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

Appendix: MO Arresters in Brief

This part of the arrester handbook explains the most important terms used in arrester technology and others associated with this technology¹.

Abnormal service conditions: are defined in IEC 60099-4, Annex A. Typical information given with enquiries and tenders is also included in IEC 60099-4, Annex G. Also see →[Normal service conditions](#).

Acceptance tests: According to IEC 60099-4, the following standard tests are carried out on MO arresters without gaps, if acceptance tests have been arranged for. They must be performed on the nearest lower whole number to the cube root of the total quantity of arresters to be supplied:

- Measurement of power-frequency voltage on the complete arrester at the →[reference current](#)
- Measurement of the →[lightning impulse residual voltage](#) on the complete arrester or on the individual →[arrester units](#), if possible at →[nominal discharge current](#)
- →[Partial discharge test](#) on the complete arrester or on the individual →[arrester units](#)
- Tightness test

Active part of an arrester: the MO resistor column(s) of an arrester, including metallic spacers and the supporting construction.

Alumina porcelain: a type of porcelain in accordance with subgroup "C 120: aluminous porcelains" of the standard IEC 60672-3.

ANSI: American National Standards Institute

Arrester disconnecter: →[Disconnecter](#)

Arrester section: →[Section of an arrester](#)

Arrester unit: →[Unit of an arrester](#)

¹ Underlined terms represent keywords (hyperlinks), which are further explained in greater detail. In the electronic version of the handbook, clicking on the terms will automatically call up the definitions.

Back flashover: flashover of a line insulator caused by the potential rise of a tower or pole during a lightning strike to the overhead ground or shield wire, or to the tower or pole itself. Back flashovers are particularly common when high tower footing impedances are present, since they cause high voltage drops during the flow of lightning discharge current. → [Line arresters](#) are a possible countermeasure.

Basic lightning impulse insulation level: → [BIL](#)

Basic switching impulse insulation level: → [SIL](#)

BIL: abbreviation for "basic lightning impulse insulation level". Even though this term is frequently used also when referring to → [IEC](#) standards, it is only defined by → [IEEE](#) and → [ANSI](#) (see standards IEEE Std 1313.1-1996, IEEE Std C62.2-1987, IEEE Std C62.22-1997, ANSI C92.1-1982). The IEC standard 60071-1, Ed. 8, 2006-01, uses the term → [standard rated lightning impulse withstand voltage](#) instead, abbreviated to → [LIWV](#).

C 110: → [Quartz porcelain](#)

C 120: → [Alumina porcelain](#)

Composite hollow core insulator: a hollow core insulator made out of an → [FRP](#) tube with applied polymeric sheds. The FRP tube can be of the → [wet-processed](#) or → [vacuum-impregnated](#) type. The sheds almost always consist of → [silicone rubber](#), with differences between → [RTV silicone rubber](#), → [HTV silicone rubber](#), and → [LSR/LR](#). They are applied using different manufacturing processes: → [push-on method](#), → [direct molding](#).

Conditioning: Conditioning is a part of the → [operating duty test](#) and takes place before the actual proof of → [thermal stability](#), after energy has been injected. It should cause possible → [electrical ageing](#) (degradation) to occur, so that the actual operating duty test is not carried out in a simplified manner on brand new MO resistors. The conditioning consists of twenty → [lightning current impulse](#) stresses of → [nominal discharge current](#), which are superimposed on an applied power-frequency voltage with 1.2 times the → [continuous operating voltage](#). For the operating duty test on arresters of → [line discharge classes](#) 2 to 5, two consecutive → [high current impulses](#) with 100 kA peak value each, are additionally applied.

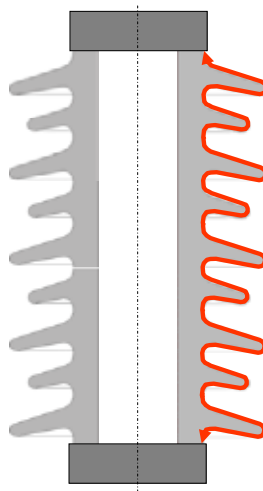
Continuous operating voltage of an arrester: (symbol: U_c) The continuous operating voltage is the designated permissible root-mean-square value of power-frequency volt-

age, which is allowed to continuously be applied between the arrester terminals (IEC 60099-4, 3.9).

Coordination withstand voltage: (symbol: U_{cw}) a term from the →[insulation coordination](#): value of the →[withstand voltage](#) of an insulation configuration in actual service conditions, for which an acceptable failure rate (the so-called "performance criterion") results. The application of surge arresters ensures that the value of the coordination withstand voltage is never exceeded at the terminals of the device to be protected. For an exact definition of the terms mentioned above, and their meaning and determination during the process of insulation coordination, see IEC 60071-1 and 60071-2.

Corona ring: electrostatic shielding of the arrester connection at the high-voltage end, to reduce the →[radio interference voltage](#) (RIV). Not to be confused with a →[grading ring](#). See the figure there.

Creepage (distance): The creepage (distance) of an insulator is the distance between the metal end fittings, measured along the housing surface (red curve in the figure). It is an important factor in the behavior of an insulator, or a device containing such an insulator in polluted conditions. See also →[guaranteed creepage distance](#), →[nominal creepage distance](#), →[specific creepage distance](#), →[unified specific creepage distance](#), →[flashover distance](#).



Current impulse: unidirectional current impulse, which ideally increases quickly to a peak value and then – generally more slowly – returns to zero. The parameters which define a current impulse are polarity, peak value, →[virtual front time](#) T_1 and →[virtual time to half-value on the tail](#) T_2 in microseconds (exception: →[long duration current impulse](#), which is characterized by polarity, peak value, virtual duration of the peak and virtual total duration). This is represented as T_1/T_2 , without information about the time

unit. For example, the → [lightning current impulse](#) ($T_1 = 8 \mu\text{s}$, $T_2 = 20 \mu\text{s}$) is described as a current of the form 8/20.

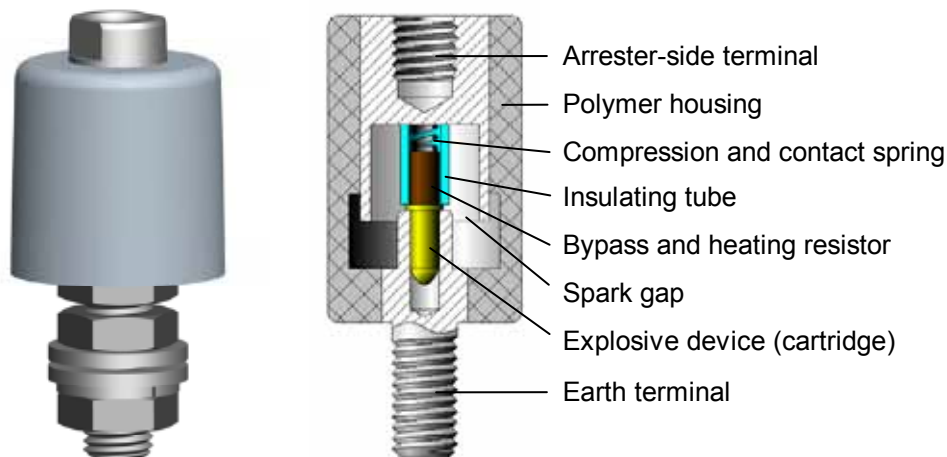
Degradation: → [Electrical ageing](#)

DIN: Abbreviation for "Deutsches Institut für Normung e.V.", a German organization for standardization based in Berlin.

Direct molding: a means of putting silicone rubber sheds on an arrester or on the FRP core of a → [composite hollow core insulator](#) or composite line insulator (as opposed to the → [push-on method](#)). In this case different technologies are utilized. Most frequently the body which is to be recast is set in a tightly closed lengthwise-divided mold, and completely recast in one pouring. This is possible and usual for lengths of up to about two meters. For even longer bodies the sheds are raised in several pourings, one after another, whereby each segment is → [vulcanized](#) to the previous one. The resulting encapsulation creates two lengthwise molding lines (frequently, but mistakenly, called "seams"). However, if this is carried out carefully, it does not negatively affect the operating behavior. In a different procedure the encapsulation is accomplished by raising the sheds one after another, by means of a one-piece form, which surrounds the body in a ring, and which is passed along the body step by step. Another known procedure is that in which the silicone rubber is raised spirally with a form which moves along the rotating body. The result is not single separate sheds, but instead one continuous spiral.

Discharge voltage: → [Residual voltage](#)

Disconnecter: a device at the earth terminal of the arrester, which separates the arrester from the system after an overloading. This is especially important in conjunction with polymer-housed arresters, since their housing does not decay during a failure, and the puncture and flashover channels as well as black carbon and burn traces then form an



earth fault (while a porcelain arrester often totally breaks apart, thereby becoming isolated from the line). Without a disconnector – at least in a solidly earthed neutral system – a subsequent operation of the appropriate line section would no longer be possible. One disadvantage, however, is that after the disconnection of the arrester – which often goes unnoticed – protection against overvoltage is no longer feasible. Disconnectors are only installed in distribution systems or in association with →[line arresters](#). One of the most common working principles of disconnectors currently being manufactured is the ignition of a small explosive device (e.g., the cartridge of a gas pistol) caused by the thermal effect of the power-frequency earth fault current, which flows after an arrester failure. The explosive device tears the surrounding polymeric housing and causes the flexible earthing lead to disconnect from the arrester:

Distributed constant impulse generator: generator to simulate the equivalent circuit of a line by distributed, series connected →[π-elements](#) (series inductors and shunt capacitors). In current impulse laboratories for arrester testing, distributed constant impulse generators are used for the →[long duration current impulse withstand test](#) (IEC 60099-4, 8.4.3), the →[line discharge test](#) (IEC 60099-4, 8.4.2) and the →[switching surge operating duty test](#) (IEC 60099-4, 8.5.5). An example of a distributed constant impulse generator is given in IEC 60099-4, Annex J.

Earth fault factor: (symbol: k , according to IEC 60071-1) at a given location, the ratio of the root-mean-square value of the highest power-frequency phase-to-earth voltage on a healthy phase during an earth fault, affecting one or more phases at any point on the system, to the root-mean-square value of the power-frequency phase-to-earth voltage which would be obtained at the given location in the absence of any such fault (IEC 60071-1, 3.15). The earth fault factor only refers to a particular point of a three-phase system, and to a particular system condition. The magnitude of the earth fault factor depends on the way the neutrals of a system are earthed: $k \leq 1.4$ for a →[solidly earthed neutral system](#), and $k \geq 1.73$ for →[resonant earthed](#) or →[isolated neutral](#) systems.

EGLA: (externally gapped line arrester) →[line arrester](#) with external serial spark gaps; the relevant test standard is IEC 60099-8.

E-J-characteristic: →[field strength-current density characteristic](#)

Electrical ageing: (also: degradation) changes (or rather, deterioration) of the →[voltage-current-characteristic](#) of an MO resistor or arrester in the →[leakage current](#) region. With the level of technology used to manufacture MO resistors today, and under energy stress within the manufacturers' specified limits, electrical ageing is not to be

expected. It can, however, occur under conditions of extraordinarily high current impulse stress. Also, certain compounds in the gaseous atmosphere surrounding the MO resistors, or other solid or liquid insulating materials in direct contact with the resistors can, through chemical influences, cause electrical ageing, if no direct measures are undertaken to prevent this during development and production of the MO resistors and the arresters. Electrical ageing is partially reversible (the voltage-current-characteristic "recovers").

Energy handling capability: → [Single impulse energy handling capability](#), → [Thermal energy handling capability](#), → [Line discharge class](#)

Fast-front overvoltageHH: transient overvoltage, normally unidirectional, with time to peak of greater than 0.1 μs up to and including 20 μs , and tail duration below 300 μs (IEC 60071-1, 3.17).

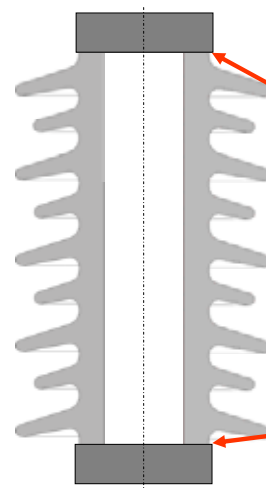
Fiber-glass reinforced plastic: (abbreviated: FRP) this material is frequently utilized in an arrester for the MO resistor column supporting construction. In polymer-housed arresters it is the most important component for achieving the mechanical strength of the housing, e.g., in the form of rods, loops, tubes or wound mats.

Field strength-current density characteristic: (also: *E-J*-characteristic) representation of the field strength (strictly speaking the voltage relative to the height) of an MO resistor system in relation to the current density. Field strength peak values are generally applied to the ordinate. The abscissa uses current density peak values (only the resistive component in the case of power-frequency current densities), using logarithmic representation and covering a range of several decimal powers. It is possible to multiply the field strength with the height, and the current density with the current cross-sectional area, to calculate the *U-I*-characteristic of an MO resistor type based on this material system.

Flashover distance: The flashover distance of an insulator is the shortest distance between its metal end fittings (red line in the figure). See also → [creepage distance](#).

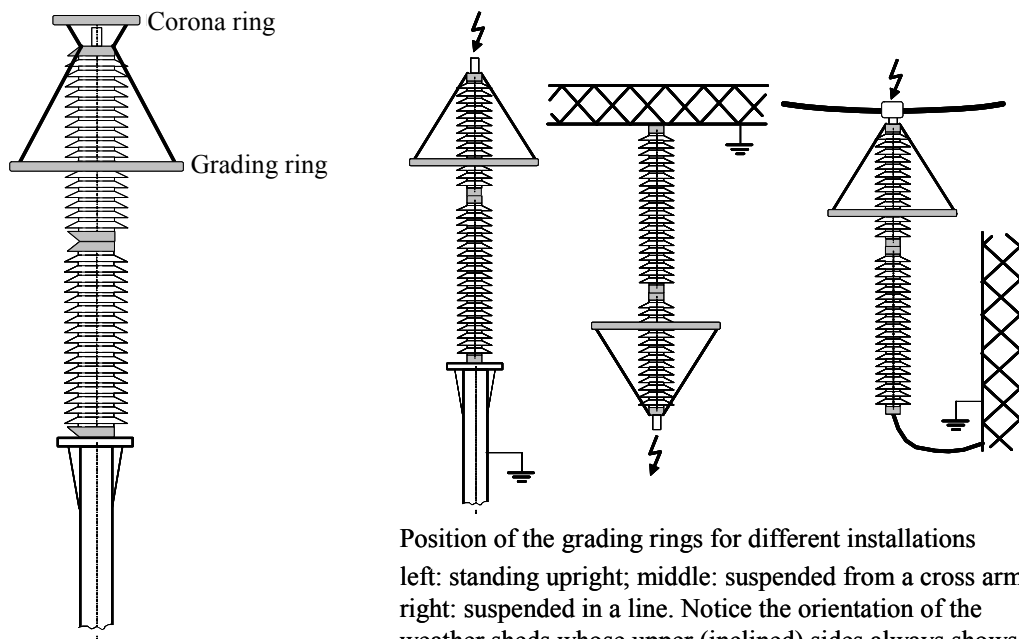
FRP: → [Fiber-glass reinforced plastic](#)

Gapped arrester: an (SiC) arrester having one or more gaps in series with one or more non-linear resistors (IEC 60099-1, 2.2). Even though there are also metal-oxide arresters with gaps, internal (IEC 60099-6) as well as external ones (→ [EGLA](#), IEC



60099-8), and even though there are also designs with shunt gaps (which are connected in parallel to the non-linear resistors), generally a "gapped arrester" is used to describe only those →[silicon-carbide](#) (SiC) arresters with internal series gaps, which were in use before the introduction of the metal-oxide arresters without gaps.

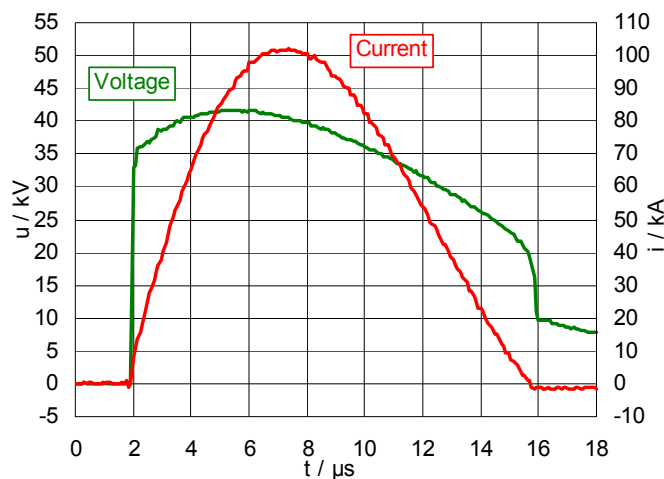
Grading ring: grading rings are used if the arrester length exceeds 1.5 to 2 meters, and usually for arresters made up of several units. They are arranged over approximately a quarter of the length of the arrester from the high-voltage flange towards the earth end, and serve to control the voltage distribution from the high-voltage end to the earth end, which is unfavorably influenced by the earth capacitances affecting the arrester. Without these countermeasures the MO resistors at the high-voltage end of the arrester would be stressed considerably more than those at the earthed end, leading to potentially excessive heating of the active part in this area. In suspended arresters, the grading rings are installed in various positions – for example the positions are different in an arrester installed on a cross arm or gantry and a →[line arrester](#) installed directly in the line, see the figure. Grading rings must not be confused with →[corona rings](#), which are only used to provide an electrostatic shield for the terminals at the high-voltage end in order to reduce the →[radio interference voltage](#).



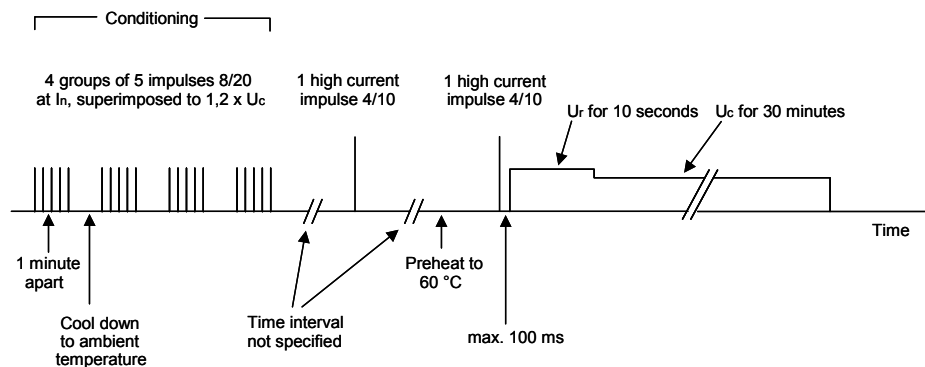
Position of the grading rings for different installations
left: standing upright; middle: suspended from a cross arm;
right: suspended in a line. Notice the orientation of the
weather sheds whose upper (inclined) sides always shows
upwards.

Guaranteed creepage distance: creepage distance of an insulator as guaranteed by the manufacturer, taking into account possible dimensional tolerances which originate in the manufacturing process; normally a few percent less than the →[nominal creepage distance](#).

High current impulse: peak value of a \rightarrow [current impulse](#) 4/10, used to test the stability of an arrester on nearby direct lightning strikes (IEC 60099-4, 3.31). It should be noted, however, that a high current impulse with an amplitude of, for example, 100 kA, has little to do with a real lightning discharge current at the same value, which can last several ten to hundred microseconds. Especially while testing arresters with MO resistors of more than 40 mm in diameter, is the high impulse current then less an energy, and much more a dielectric stress (because of the extraordinarily high \rightarrow [residual voltage](#)). High current impulses are needed in the laboratory for the \rightarrow [operating duty tests](#) on arresters or \rightarrow [arrester sections](#). They are produced by a capacitor discharge in an aperiodically damped RLC circuit. The current amplitude is within a range of 10 kA to 100 kA (see IEC 60099-4, Table 6). The following oscillogram illustrates an example of a high current impulse test on an arrester section at a current amplitude of 100 kA:



High current impulse operating duty test: see IEC 60099-4, 8.5.4. To be carried out on all arresters with \rightarrow [nominal discharge current](#) of 1.5 kA, 2.5 kA or 5 kA and on arresters with nominal discharge current of 10 kA and \rightarrow [line discharge class](#) 1. The sequence is schematically depicted in the diagram following at the end of this paragraph. Also the 20-kA High Lightning Duty arresters for the voltage range 1 kV to 52 kV are subjected to a high current impulse operating duty test. However, it is carried out in a different sequence (see IEC 60099-4, Annex C).



Highest system voltage: → [Highest voltage of a system](#)

Highest voltage for equipment: (symbol: U_m) root-mean-square value of the highest phase-to-phase voltage for which the equipment is designed with reference to its insulation and other characteristics, which relate to this voltage in the relevant equipment standard (IEC 60071-1, 3.10).

Highest voltage of a systemHH: (symbol: U_s) root-mean-square value of the highest phase-to-phase operating voltage, which occurs under normal operating conditions at any time and at any point in the system (IEC 60071-1, 3.9).

HTV silicone rubber: High temperature vulcanizing silicone rubber. A single component type of → [silicone rubber](#), which is delivered in extremely high viscous conditions (comparable to natural rubber). It is injected into the mold under high pressures (several ten MPa) and temperatures ($> 150^\circ\text{C}$) and finally → [vulcanized](#) at similarly high temperatures.

Hydrophobicity: the characteristic of repelling water. No closed water film can form on a hydrophobic surface. Instead water on the surface pulls together to form single droplets and drips off the surface. According to a proposal of the Swedish Transmission Research Institute ("STRI guide 92/1: Hydrophobicity classification guide"), the degree of hydrophobicity is divided into seven classes (HC 1 to HC 7), where HC 1 corresponds to a completely hydrophobic and HC 7 to a completely hydrophilic (easily wetted) surface. This classification has been adopted by the IEC: IEC TS 62073, First Edition, 2003-06 "Guidance on the measurement of wettability of insulator surfaces" (refer to this for further information on hydrophobicity). However, the hydrophobicity classes are referred to there as "WC" (for wettability class). A material for which hydrophobicity is particularly characteristic is → [silicone rubber](#).

IEC: Abbreviation for "International Electrotechnical Commission". Commission for the worldwide standardization in the area of electrotechnology, with headquarter in Geneva, Switzerland.

IEEE: Abbreviation for "Institute of Electrical and Electronics Engineers", an American organization which, besides other tasks, develops standards on the field of electrical and information technology, based in New York City, USA.

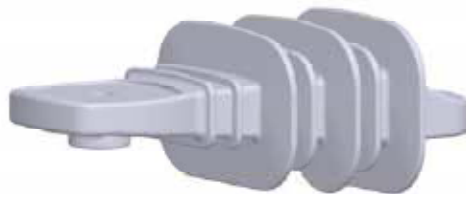
Impedance earthed neutral system: a system in which one or more neutral points are earthed through an impedance to limit earth fault currents (IEC 60071-1, 3.13).

I_n : → [Nominal discharge current](#)

Inductance of an arrester: MO resistors, when stressed by otherwise equal current amplitudes, exhibit increasing residual voltage with greater front steepness of the current impulse. Thus, in the case of → [steep current impulse](#) stress, a 5% increase in residual voltage is expected compared with that under equally high [lightning current impulse](#) stress. In addition, however, for very short rise times of the discharge current (front times of less than about 1 μ s) inductive voltage drops due to the spatial expansion of the arrester, must be taken into account. For outdoor arresters the inductance of a straight, stretched line with large clearance to other lines or earthed parts may be assumed. An arrangement like this has an inductance of about 1 μ H/m. At the same time, only 0.3 μ H/m is effective for a gas-insulated, metal-enclosed arrester because of its coaxial design. When viewing the protective level for steep current impulse stress in its entirety, the inductance of the connecting leads between overhead line conductor and arrester high-voltage terminal, as well as between its earthing terminal and effective station earth, must also be considered (see [Figure 6](#)).

Insulation coordination: the selection of the dielectric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended, while taking the service environment and the characteristics of the available overvoltage protective devices into account (IEC 60071-1, 3.1).

Insulating clamp: an insulated clamp used in the medium-voltage system to fit arresters with disconnectors. Following an arrester failure, the insulating clamp must be



able to withstand the line-to-earth voltage (the failed arrester is effectively a short-circuit) until the arrester is replaced. The figure illustrates a polymer-type insulating clamp. In the case of → [medium-voltage arresters with porcelain housing](#), metal clamps are often placed around to porcelain housing for this purpose, see the figure there.

I_s : → [Rated short-circuit \(withstand\) current](#)

Isokeraunic line: lines of equal → [keraunic level](#) in a map

Isolated neutral system: a system in which the neutral points are not intentionally earthed, except for high impedance connections for protection or measurement purposes (IEC 60071-1, 3.11).

Keraunic level: (frequently, but mistakenly called isokeraunic level) the average number of thunderstorm days per year. From the keraunic level the ground flash density and consequently the expected arrester stress in the system can be deduced.

K_s : → [Safety factor \$K_s\$](#)

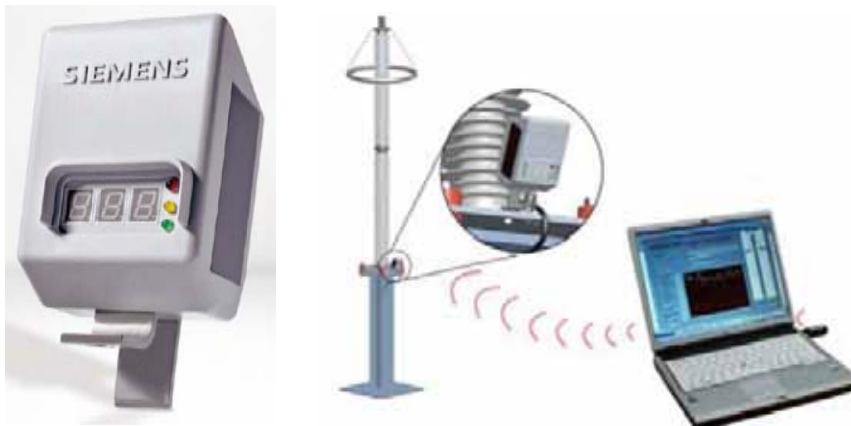
Leakage current: current which flows through the arrester at continuously applied power-frequency voltage. At alternating voltage it consists of a strongly capacitive and a considerably smaller resistive component, both of which depend on the MO resistors used. The capacitive part is heavily affected by stray capacitances and therefore also depends on the actual location of the arrester and on its overall dimensions. The peak value of the leakage current, as measured on site, is usually within the range of 0.5 mA to 2 mA, depending on the type of MO resistors and the specific way of installation.

Leakage current monitor: a device attached to the outside of the arrester (see picture), which measures the → [leakage current](#) flowing through the arrester. Usually the peak value of the current is recorded. Either the peak value itself or an apparent root-mean-

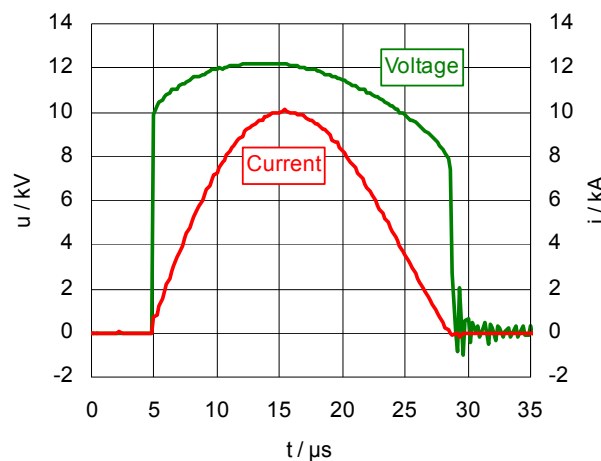


square value over a scaling factor is indicated. Most leakage current indicators are combined with a → [surge counter](#) in the same housing (see picture). Leakage current monitors are series-connected with the arrester in its earth connection. This requires installation of the arrester isolated from the ground by means of insulating feet. Recent developments of leakage current monitors are based on the analysis of the third harmonic in the leakage current, which is used to evaluate the resistive component. Built-in electric

field sensors compensate for the influence of the third harmonic in the voltage, which can seriously distort the measurement. The figure below shows such a system, powered locally using solar modules, which displays the leakage current digitally and also has a "traffic light function" ("OK" – "Warning" – "Alarm"). The readings can be sent over a wireless interface to a USB stick, from where they can be further analyzed and archived on a computer. For more information about arrester monitoring, see IEC 60099-5.



Lightning current impulse: → [current impulse](#) 8/20 with a → [front time](#) between 7 μs and 9 μs and a → [time to half-value on the tail](#) between 18 μs and 22 μs (IEC 60099-4, 3.17). Lightning current impulses are used in the laboratory to ascertain the → [voltage-current-characteristic](#) of arresters, → [arrester sections](#) or → [MO resistors](#), as well as during the → [conditioning](#) as part of the → [operating duty test](#). They are produced by a capacitor discharge in an aperiodically damped RLC circuit. The current amplitudes are within a range of 100 A to 40 kA. The oscillogram depicts an example of a residual voltage measurement on an MO resistor at a lightning current impulse of 10 kA.



Lightning impulse protective level: maximum value of the →[residual voltage](#) of an arrester at →[nominal discharge current](#).

Lightning impulse residual voltage: →[residual voltage](#) of an arrester, →[arrester unit](#), →[arrester section](#) or →[MO resistor](#) at →[lightning current impulse](#).

Lightning overvoltage: transient overvoltage caused by direct lightning strike to an overhead line conductor, a shield wire or a tower, or induced by lightning currents in neighboring lines or metal structures. Most of the lightning strikes (80% ... 90%) have a negative polarity. The currents are normally within the range of 30 kA to 50 kA, with measured maximum values of more than 300 kA. The front time is only a few microseconds, the total duration about 10 µs to 100 µs. Normally a lightning flash consists of multiple strikes, which occur at intervals of about 5 ms to 200 ms, using the same path as the initial strike. The level of overvoltage caused by a lightning strike results from the lightning current impulse flowing through the conductor and the →[surge impedance](#) of the line and amounts to several million volts. However when a flashover occurs across a line insulator, the level is actually limited to the value of the insulator flashover voltage. Only these overvoltages run into the substation and have to continue to be limited by the arresters installed there. Lightning overvoltages usually belong to the class of →[fast-front overvoltages](#), according to IEC 60071-1.

Line arrester: also: transmission line arrester (TLA) or transmission line surge arrester (TLSA); arrester which is installed in an overhead line in parallel to a line insulator to prevent flashovers of the insulator. Line arresters are preferably installed where frequent →[back flashovers](#) occur due to missing or inadequate overhead ground or shield wire protection and/or high tower footing impedances (e.g. in rocky terrain). In order to improve the supply quality of an already existing transmission or distribution line, installing line arresters on all, or only on some, of the towers or poles is in many cases a cost-saving alternative to improving the shielding of the line or the grounding of towers or poles. Line arresters are used not only in gapless technology, but also in conjunction with an external serial spark gap, which insulates the arrester from the line during normal operation, switching overvoltages and after overloading. The terms [NGLA](#) (non-gapped line arrester) and [EGLA](#) (externally gapped line arrester) are now in widespread use.

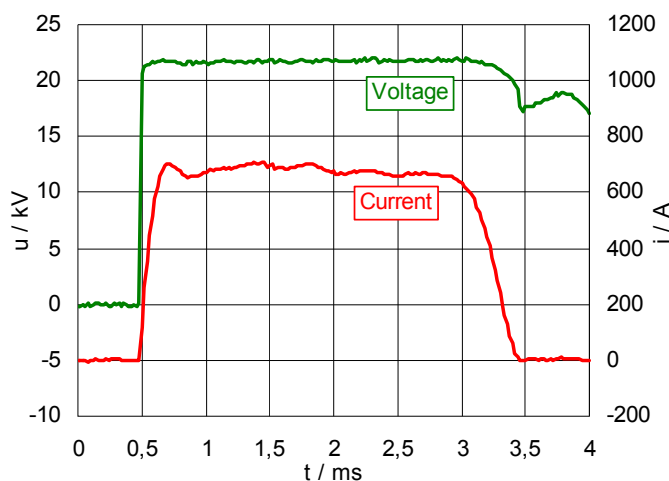
Line discharge class: The line discharge class is the only possibility in IEC 60099-4 to specify the energy handling capability of an arrester. There are five line discharge classes (1 to 5) which are defined by increasing demands on the energy handling capability. They differ according to the testing parameters in the →[line discharge test](#)

(IEC 60099-4, Table 4). The →[thermal energy handling capability](#) of an arrester can be derived from its line discharge class in conjunction with the →[switching impulse residual voltage](#) (see IEC 60099-4, Annex E). Also see [Figure 21](#) with the accompanying explanation.

Line discharge test: The line discharge test is a special form of the →[long duration current impulse withstand test](#). In this test (IEC 60099-4, 7.4.2), an arrester, an →[arrester section](#), or a single →[MO resistor](#) is exposed to 18 →[long duration current impulses](#), which are in detail specified in IEC 60099-4, Table 4. The test is considered passed if the resistors show no evidence of puncture, flashover, cracking or other significant damage and their →[lightning impulse residual voltage](#) at →[nominal discharge current](#) has not changed by more than 5%.

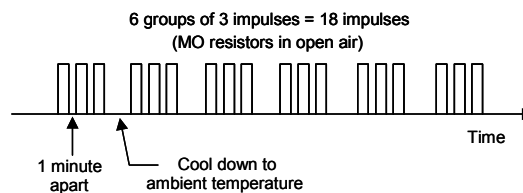
LIWV: abbreviation for →["standard rated lightning impulse withstand voltage"](#) as defined in IEC 60071-1. Equivalent to →[BIL](#) in the American →[IEEE](#) standards.

Long duration current impulse: → a rectangular current impulse, which quickly rises to its maximum value, remains substantially constant for a specified time period, and then quickly falls to zero. Characteristic parameters of a long duration current impulse include polarity, peak value, virtual duration of the peak and virtual total duration (IEC 60099-4, 3.18). Long duration current impulses are needed in laboratories for the →[long duration current impulse withstand test](#) and the →[switching surge operating duty test](#) on individual →[MO resistors](#), →[arrester sections](#) or arresters. They are usually generated by the discharge of a →[distributed constant impulse generator](#), which is made up of capacitors and air-core inductors. The current impulses have peak values of up to 2 kA and virtual total durations of up to several milliseconds. The following oscillogram depicts an example of a long duration current impulse withstand test on an arrester section with a current peak value of about 700 A and a virtual duration of the peak of 2.4 ms (corresponds to the typical current form of a →[line discharge test](#) for →[line discharge class 3](#)):



Long duration current impulse withstand capability: This is not a standard IEC 60099-4 term. It is, however, listed by practically all the manufacturers, since it is a good measure of the →[single impulse energy handling capability](#) (which is also not defined in IEC 60099-4). It is generally common to list the long duration current impulse withstand capability as a maximum permitted →[long duration current impulse](#) of a virtual duration of peak of 2 ms or 2.4 ms. At this current single MO resistors are stressed eighteen times in succession following the test specification of the →[long duration current impulse withstand test](#). The test is considered passed if the resistors show no evidence of puncture, flashover, cracking or other significant damage and their →[lightning impulse residual voltage](#) at →[nominal discharge current](#) has not changed by more than 5%.

Long duration current impulse withstand test: This test, according to IEC 60099-4, 8.4.3, serves – indirectly – as a proof of the →[single impulse energy handling capability](#), though this is not defined in the IEC standard. The test is carried out on individual MO resistors in open air according to the following diagram:



The test is considered passed if the resistors show no evidence of puncture, flashover, cracking or other significant damage and their →[lightning impulse residual voltage](#) at →[nominal discharge current](#) has not changed by more than 5%.

Low short-circuit current: →[Short-circuit tests](#)

LR: →[LSR](#)

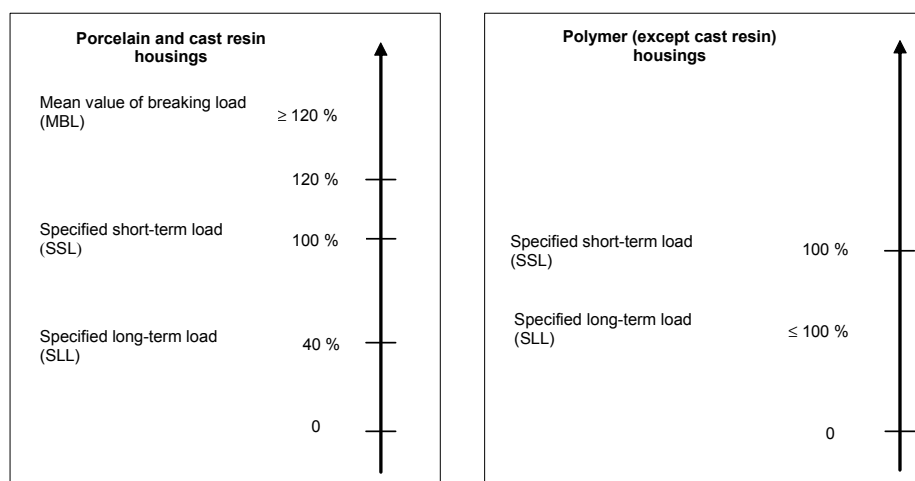
LSR: (also known as LR) abbreviation for liquid silicone rubber. A type of silicone rubber which is delivered in a state of medium viscosity. It is mixed out of two components in more or less equal parts and can be filled into molds under moderate pressure at process temperatures ranging from 110 °C to 200 °C. LSR is increasingly replacing the widely used →[RTV silicone rubber](#), since it is more economical to purchase and process and has similarly good operating characteristics.

MBL: →[mean breaking load](#).

MCOV: (abbreviation for: maximum continuous operating voltage) a term which is only defined in the American arrester standard IEEE Std C62.11-1999 as "the maximum designated root-mean-square (r.m.s.) value of power-frequency voltage that may be applied continuously between the terminals of the arrester". Corresponds to the [continuous operating voltage](#) U_c , according to IEC 60099-4.

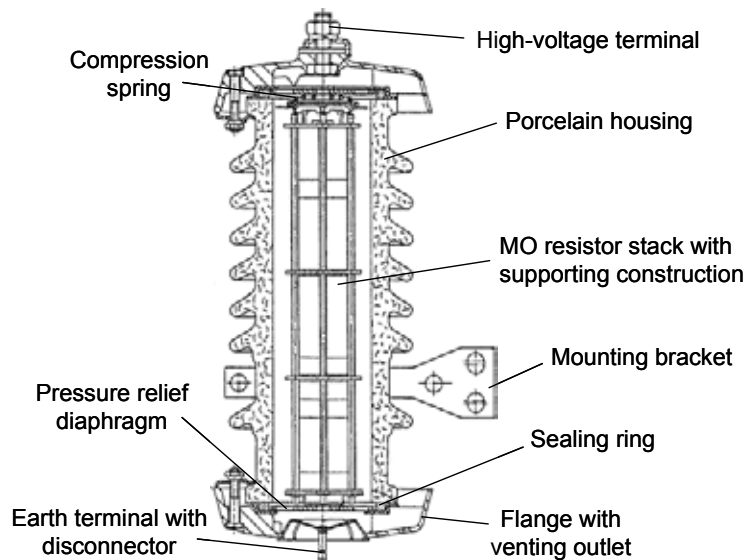
Mean breaking load: (MBL) mean breaking load for arresters with porcelain or cast resin housing, established in tests. See also → [Mechanical loads](#).

Mechanical loadsH: static and dynamic loads are defined in IEC 60099-4, as shown in the figure. Whereas the indicated specifications are currently undisputed for porcelain housings, this is not the case for the various types of polymer-housed arresters, in which the active part is sometimes integrated with the housing and thus part of the mechani-



cally supporting structure. At present, it is up to the manufacturer to decide how to specify the loads. IEC 60099-4 only defines how the specified loads are to be demonstrated in the type test. Cast resin housings resemble porcelain housings in terms of their mechanical properties (i.e. they are brittle), so they are treated in exactly the same way in the standard. → [Specified long-term load](#) → [SLL](#) → [Specified short-term load](#) → [SSL](#) → [Mean breaking load](#).

Medium-voltage arrester with porcelain housing: manufacture of this type of arrester has virtually ceased, although large numbers are still in service. As shown in the diagram, they contain almost all the design features that are described in general terms in the section of this book covering arresters with porcelain housing. Low manufacturing costs are even more critical for medium-voltage arresters than for high-voltage arresters, but even so, the sealing system must meet the highest possible standards. The enormous cost pressure means that quality has not always been given top priority, and poor sealing



is a common cause of failure in the medium-voltage range everywhere in the world – one of the reasons behind the drive to switch to polymer housings in the mid 1980s (although even leaving aside sealing issues, medium-voltage arresters have significantly higher failure rates than high-voltage arresters because they are subject to more frequent energetic overload from lightning strikes close to the arrester). In principle, a medium-voltage arrester with porcelain housing has the same sealing system as a high-voltage arrester. The same principle is applied and the same materials are used, and because the same pressure relief principle is used, the overload behavior is as described for high-voltage arresters. However there used to be many types of medium-voltage arrester with porcelain housing that lacked a pressure relief device – and some are still in service to this day. This was disputable even in those days and must now, finally, be characterized as outdated.

Metal-oxide arrester: (more precisely: non-gapped metal-oxide arrester) an arrester with non-linear (voltage-dependent) → [metal-oxide resistors](#), which are connected in series or in parallel without any integrated series or parallel gaps (IEC 60099-4, 3.1).

Metal-oxide resistor: (MO resistor) resistor with an extremely non-linear voltage-current-characteristic. All resistors currently designated as metal-oxide resistors consist of about 90% zinc-oxide (ZnO; consequently, the metal-oxide arrester is occasionally called a ZnO arrester). The other 10% is composed of about 10 different additives in the form of the oxides of rare earths (Bi, Sb, Co, Mn), which finally make up anywhere between a few ppm and up to a few percent of the total mass. The components are carefully milled into powder and mixed. A slurry is prepared from the powder, which is granulated and pressed into cylindrical (sometimes also toroidal) forms, dried and then sintered to a homogenous ceramic at temperatures of up to 1200 °C. The end faces are

lapped or grinded, afterwards plated with aluminum or zinc, and finally the circumference is coated (e.g., glazed). The common dimensions of metal-oxide resistors currently being manufactured include diameters of between about 30 mm and 100 mm; the height is at the most ca. 45 mm.

Metal-oxide surge arrester: → [Metal-oxide arrester](#)

MO arrester: → [Metal-oxide arrester](#)

MO resistor: → [Metal-oxide resistor](#)

Monitoring spark gap: a device which is attached to the outside of the arrester, whose removable control electrodes record, by means of sparkover marks, the number, intensity (amplitude and duration) and polarity of arrester operations. Monitoring spark gaps are series-connected with the arrester in its earth connection. This requires installation of the arrester isolated from the ground by means of insulating feet. The three pictures show a monitoring spark gap mounted on an arrester (top left), in opened condition with the control electrodes removed (top right), as well as examples of sparkover marks on the control electrodes (below).



MOSA: → [Metal-oxide arrester](#)

Nearby direct lightning strike: This term, in the arrester context, refers to lightning which directly strikes an overhead line conductor at a point which is so close to an arrester that an insulator flashover does not occur before the overvoltage surge – in the

form of a traveling wave – reaches the arrester. This frequently happens in distribution systems and usually destroys the affected arrester. Arresters – particularly station arresters – are normally configured with the assumption that the greatest part of the contained charge in the lightning discharge is already diverted to ground by means of flashed over line insulators before it reaches the arrester.

NEMA: Abbreviation for "National Electrical Manufacturers Association", an American organization for developing standards for the electrical manufacturing industry, based in Rosslyn, Virginia, USA.

Neutral earthing of a system: Power transmission and distribution systems, depending on how the neutral points are connected to earth (if at all), are categorized into →[isolated neutral systems](#), →[solidly earthed neutral systems](#), →[impedance earthed neutral systems](#) and →[resonant earthed neutral systems](#).

NGLA: non-gapped →[line arrester](#). Covered by the standard IEC 60099-4.

Nominal creepage distance: the creepage distance assigned to an insulator. The actual creepage distance may deviate by a few percent more or less, as a result of manufacturing tolerances. Also see →[guaranteed creepage distance](#).

Nominal discharge current^{HH}: the peak value of a →[lightning current impulse](#) which is used to classify an arrester. IEC 60099-4 lists five different possible nominal discharge current values: 1.5 kA, 2.5 kA, 5 kA, 10 kA and 20 kA. For distribution arresters the nominal discharge current can be taken as a direct measure of the energy handling capability. For high-voltage arresters the operating characteristics are not fully described by the nominal discharge current. Further parameters must be considered as well, such as the →[line discharge class](#).

Nominal system voltage: →[Nominal voltage of a system](#)

Nominal voltage of a system: a suitable approximate value of voltage used to designate or identify a system (IEC 60071-1, 3.8). Also see →[highest voltage of a system](#), →[highest voltage for equipment](#).

Normal service conditions: According to IEC 60099-4, 5.4.1, the following conditions are considered to be normal service conditions:

- Ambient air temperature within the range of -40° C to +40° C
- Solar radiation 1.1 kW/m²
- Altitude not exceeding 1000 m above sea level

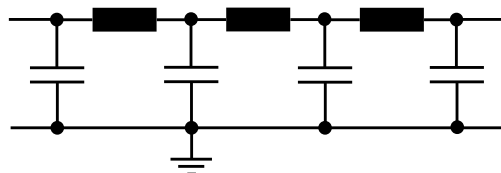
- Frequency of the a.c. power supply not less than 48 Hz and not exceeding 62 Hz
- Power-frequency voltage applied continuously between the terminals of the arrester not exceeding the arrester's continuous operating voltage
- Wind velocity ≤ 34 m/s
- Vertical mounting of the arrester

Also see → [abnormal service conditions](#).

Operating duty test^{HH}: In the operating duty tests (IEC 60099-4, 8.5) it is proved that after energy has been injected, the arrester remains → [thermally stable](#) (i.e., cools back down to normal operating temperature) under the conditions of simultaneously occurring → [temporary overvoltage](#). The test parameters are chosen to reflect worst case conditions with regard to possible → [electrical ageing](#) (degradation) of the MO resistors and to the ambient and the operating temperature. The operating duty test may be carried out on → [arrester sections](#), which represent the actual arrester with regard to the electrical and thermal behavior (→ [thermally equivalent prorated section](#)). Distinctions are made between the → [high current impulse operating duty test](#) and the → [switching surge operating duty test](#).

Partial discharge test: This test proves that when a voltage of 1.05 times the → [continuous operating voltage](#) is applied, the arrester is sufficiently free of internal partial discharges. According to the currently applicable IEC 60099-4, Ed. 1.1, 1998-08, "sufficiently free" means a partial discharge level of ≤ 10 pC. The partial discharge test is part of the → [type tests](#), and is one of the most important → [routine tests](#). It is also defined as an → [acceptance test](#).

Pi-element: (π -element) A segment of an electrical equivalent circuit is designated as π -element when it is made up of one series element in the line and two parallel elements located in front of it and behind it, which are connected between the line and the ground reference. When disregarding losses, a power transmission or distribution line can be represented as a series connection of π -elements, whose series elements consist of inductances and whose parallel elements consist of capacitances to earth, see diagram:



Pollution level: a measure of the degree of pollution to which resources at a location are subject. The pollution levels defined in IEC 60815-1, Ed. 1.0, 2008-10 are shown in the table below. Depending on the pollution level, IEC 60815-2 (for porcelain and glass

arresters) and IEC 60815-3 (for polymer insulators) recommend the indicated →[unified specific creepage distance](#) (USCD), but this must then be corrected for the particular insulator. For the sake of completeness, the converted values for the →[specific creepage distance](#) (SCD) are also shown as defined in the previous version of the standard, IEC 60815 Ed. 1, 1986 (SCD and USCD values are, per definition, differing by the factor $\sqrt{3}$). The pollution levels were also defined differently in the previous version: "I" – "light", "II" – "medium", "III" – "heavy", "IV" – "very heavy", and the recommendations for porcelain insulators were: "I" – SCD = 16 mm/kV; "II" – SCD = 20 mm/kV; "III" – SCD = 25 mm/kV; "IV" – SCD = 31 mm/kV.

Level	Definition	USCD mm/kV	(SCD) mm/kV
a	very light	22	12.7
b	light	27.8	16
c	medium	34.7	20
d	heavy	43.3	25
e	very heavy	53.7	31

Portland cement: a type of cement which is, for example, used to fix the metal end fittings and flanges of porcelain long-rod and hollow core insulators. Since corrosion appears when in contact with aluminum, an interface layer or coating (e.g., bitumen) must be applied before the embedding if aluminum flanges are used. This can be avoided by using →[sulfur cement](#).

Power-frequency voltage versus time characteristic: (also: U - t -characteristic or V - t -characteristic) representation of the dependency of applied permissible power-frequency voltage on permissible time duration. The voltage is referred to as the root-mean-square value related to the rated or to the continuous operating voltage. The time axis is logarithmically scaled and extends, for example, over a time range of 100 ms to 1000 s. See [Figure 20](#) for an example of a power-frequency voltage versus time characteristic.

Pressure relief class: according to earlier editions of the standard IEC 60099-4 (for gapless MO arresters) and IEC 60099-1 (for gapped SiC arresters), the root-mean-square value of the symmetrical highest short-circuit current (given in kiloamperes, partly also in letters from A to D), which can flow after an arrester has been overloaded, without causing violent shattering of the housing. The pressure relief class has now been replaced by the →[rated short-circuit \(withstand\) current](#). The short-circuit (or pressure relief) behavior is proved by means of the →[short-circuit tests](#) (formerly: pressure relief tests). Also see →[short-circuit withstand \(capability\)](#).

Pressure relief tests: → [Short-circuit tests](#)

Primer: a chemical fluid, which is applied before → [silicone rubber](#) is molded onto other components, and which brings about a strong chemical bonding between the silicone rubber and any other material (aluminum, → [FRP](#), → [MO resistors](#)) after → [vulcanizing](#).

Propagation rate of a → [traveling wave](#): the propagation rate of an electro-magnetic wave on a line is

$$v = \frac{1}{\sqrt{\varepsilon_r \cdot \mu_r}} \cdot \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}} = \frac{1}{\sqrt{\varepsilon_r \cdot \mu_r}} \cdot c_0$$

where

ε_r ... Relative permittivity of the surrounding medium

μ_r ... Relative permeability of the surrounding medium

ε_0 ... Vacuum permittivity, $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m

μ_0 ... Vacuum permeability, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m

c_0 ... Speed of light, $c_0 \approx 3 \cdot 10^8$ m/s or 300 m/μs

This means that an electro-magnetic wave (traveling wave) in an overhead line ($\varepsilon_r = 1$, $\mu_r = 1$) propagates at the speed of light ($v = 300$ m/s), but in a cable, depending on its insulation ($\varepsilon_r = 2 \dots 4$, $\mu_r = 1$), at (0.5...0.7) times the speed of light ($v = 150 \dots 210$ m/s).

Protective level of an arrester: maximum value of the → [residual voltage](#) of an arrester at a standard → [current impulse](#). In this case there is a difference between the → [lightning impulse protective level](#), the → [switching impulse protective level](#) and the → [steep current impulse protective level](#).

Protective zone of an arrester: (equivalent IEEE term: separation distance) An arrester generally has a limited protective zone of only a few meters to up to several ten meters, where the protective zone is defined as the maximum separation distance for which the insulation coordination requirements are fulfilled for a given → [arrester protective level](#) and → [coordination withstand voltage](#) (IEC 60099-5, 4.3.1). Arresters, therefore, should be installed as close as possible to the device to be protected. Since → [fast-front overvoltages](#) spread out over the line in the form of → [traveling waves](#), the voltage at the terminals of the device to be protected can be considerably higher than the → [residual voltage](#) of the assigned arrester. The arrester is "effective" only after a time interval, which depends on the propagation rate of the traveling wave and the distance, that is, the propagation time between the arrester and the device to be protected. The steepness

of the overvoltage also has a decisive effect. Generally, the protective level and the location of the arrester must be coordinated in such a way that the →[coordination with-stand voltage](#) of the device to be protected is not exceeded. See IEC 60099-5, 60071-1 and 60071-2 for details on the procedure. The protective zone of an arrester, for the simple arrangement of a transformer connected to the end of a single feeder, can be estimated with the use of the following rule-of-thumb formula:

$$x_s = \frac{\frac{\text{LIWV}}{1.15} - u_{\text{pl}}}{2 \cdot s} \cdot v$$

with x_s protective zone in m

LIWV standard lightning impulse withstand voltage of the device to be protected in kV

u_{pl} lightning impulse protective level of the arrester in kV

s front steepness of the lightning overvoltage in kV/μs (typical value: 1000 kV/μs)

v propagation speed of a traveling wave in m/μs
(overhead line: $v = c_0$ (velocity of light) = 300 m/μs;
cable: $v \approx 150 \dots 210$ m/μs)

Accordingly, when considering the connection of the equipment to an overhead line, this roughly results in a maximum protective zone of about 67 m for a solidly earthed 420-kV-system (LIWV = 1425 kV, $u_{\text{pl}} \approx 800$ kV), while for a 24-kV resonant earthed distribution system (LIWV = 125 kV, $u_{\text{pl}} = 80$ kV), the protective zone is only slightly more than four meters! Also, see [Figure 5](#) with the accompanying example.

Push-on method: a method of equipping the →[FRP](#) rods (when manufacturing composite long-rod line insulators) or FRP tubes (when manufacturing →[composite hollow core insulators](#)) with →[silicone rubber](#) sheds. Normally two procedures are common:

- 1) Onto the FRP core a smooth cover out of the same or a similar material as that of the sheds is molded, extruded or shrunken on. After that, pre-manufactured sheds are pushed on. The number of sheds and their distance to each other depends on the creepage path requirements.
- 2) Pre-assembled sheds are pushed directly onto the FRP core. There are no gaps between the sheds, instead they overlap at the ends like shingles.

By using →[primers](#), interlayers of →[RTV silicone rubber](#) and heating it afterwards in an oven, a bonding of the sheds to the core and to each other, respectively, is produced, which is nearly impossible to detach. Designs exist, however, in which the sheds are

only pushed on in an expanded condition, and which only because of the mechanical strain remain attached to the core.

Quartz porcelain: a type of porcelain in accordance with subgroup "C 110: siliceous porcelains" of the standard IEC 60672-3.

Radio interference voltage: (RIV) a voltage, given in microvolts and measured using an interference voltage measuring receiver, caused by external electrical partial discharges ("corona") at the arrester components at high potential (mainly the flange and connection at the high-potential end). Arresters with $U_r \geq 77$ kV must undergo a test to ensure that a radio interference voltage level of $2\,500\ \mu\text{V}$ is not exceeded for $U = 1.05 \cdot U_c$ (IEC 60099-4, 6.15 and 8.12). One way to reduce the radio interference voltage level is to use →[corona rings](#). Otherwise, the "usual" high-voltage optimizations must be carried out (avoiding sharp edges, increasing rounding radii, using electrostatic shielding effects).

Ranges of highest voltage for equipment: According to IEC 60071-1, 4.8, the standard highest voltages for equipment are categorized into two ranges:

- Range I: $1\text{ kV} \leq U_m \leq 245\text{ kV}$
- Range II: $U_m > 245\text{ kV}$

Rated short-circuit (withstand) current: the root-mean-square value of the symmetrical highest short-circuit current that can flow after an arrester has been overloaded, without causing violent shattering of the housing. Symbol I_s . Replaces the former →[pressure relief class](#) of the earlier editions of the IEC standard, 60099-4. This behavior is proved by means of the →[short-circuit tests](#) (formerly: pressure relief tests).

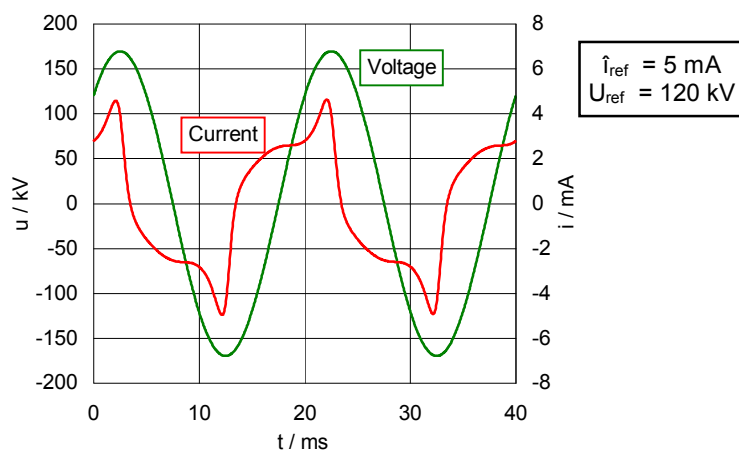
Rated voltage of an arrester: (symbol: U_r) maximum permissible root-mean-square value of power-frequency voltage between the arrester terminals at which it is designed to operate correctly under →[temporary overvoltage](#) conditions as established in the →[operating duty tests](#). Normally, the manufacturer specifies whether it can be applied to the arrester for a duration of 10 seconds (which corresponds to the value in the operating duty test) or 100 seconds. The rated voltage is the reference parameter for determining the operating characteristics (IEC 60099-4, 3.8).

Rectangular current impulse: →[Long duration current impulse](#)

Reduced short-circuit current: →[Short-circuit tests](#)

Reference current: the peak value of a power-frequency current (in the case of asymmetrical current, the higher peak value of the two polarities), through which the →[reference voltage](#) is ascertained. The reference current is specified by the manufacturer for every MO resistor type, and can be found within a range of about 0.5 mA to 10 mA. It should be selected such that it is large enough for the peak value to clearly be caused by the resistive component in the leakage current, so that the reference voltage reading is not influenced by stray capacitances. An example of a reference voltage reading at reference current can be found under →[reference voltage](#).

Reference voltage: (symbol: U_{ref}) the peak value of power-frequency voltage divided by $\sqrt{2}$ between the arrester terminals while the →[reference current](#) is flowing. The reference voltage is used when choosing a test sample and determining the test parameters for the →[operating duty test](#). In the →[routine test](#) it serves as a simple, indirect proof that an arrester or an →[arrester unit](#) was assembled in accordance with the residual voltage requirements (the respective residual voltages and the reference voltages form a fixed ratio). The following oscillogram gives an example of a reference voltage reading on an arrester unit during a routine test:



Required withstand voltage: (symbol: U_{rw}) a term from the →[insulation coordination](#): the test voltage that the insulation must withstand in a standard withstand test to ensure an acceptable failure rate (the so-called "performance criterion") in actual service conditions. For an exact definition of the term and its meaning and determination during the process of insulation coordination, see IEC 60071-1 and 60071-2. Also see →[safety factor Ks](#).

Residual voltage: the voltage drop between the terminals of the arrester when injecting a →[current impulse](#). For current impulses which have the shape and value of a standard test current impulse (→[lightning current impulse](#), →[switching current impulse](#), →[steep](#)

[current impulse](#)), the simultaneously occurring residual voltages are the [→protective levels](#) which are assigned to this current shape and value.

Resonant earthed (neutral) system: a system, in which one or more neutral points are earthed through a reactance. As a result the capacitive component of a single-phase-to-earth fault is, for the most part, compensated (which is the reason that the term "compensated system" is also common). With resonant earthing, the residual current in a fault is limited to a value at which a burning arc in the air normally self-extinguishes (IEC 60071-1, 3.14).

RIV: [→radio interference voltage](#)

Routine tests: According to IEC 60099-4, MO arresters without gaps must be subjected to at least the following routine tests:

- Measurement of the [→reference voltage](#)
- [→Residual voltage](#) test (on the complete arrester, [→arrester units](#) or samples comprising one or more [→MO resistors](#))
- [→Partial discharge test](#)
- Tightness test
- Current sharing test (in case of multi-column arresters)

RTV silicone rubber: room temperature vulcanizing silicone rubber. A type of silicone rubber which is delivered in a state of low viscosity. It is mixed out of two components in greatly differing quantitative ratios and can be filled into molds without any pressure at process temperatures starting from room temperature. The [→vulcanizing](#), however, usually occurs at higher temperatures, in order to reduce the processing time. Increasingly being replaced by [→LSR](#) (or LR).

Safety factor K_s : a factor by which the [→coordination withstand voltage](#) must be multiplied, to obtain the [→required withstand voltage](#) of a device (and, consequently, its [→standard withstand voltage](#)). Stated simply, it is necessary to ensure that no voltage occurs on the terminals of the equipment, that is higher than its standard withstand voltages, divided by the safety factor, K_s . Arresters usually protect non-self-restoring insulations (an exception are, for example, [→line arresters](#)). In these cases $K_s = 1.15$ applies. Thus, for example, to protect a transformer, which has a [→standard lightning impulse withstand voltage](#) of 1425 kV in a system with $U_s = 420$ kV, the [→lightning impulse protective level](#) and the location of the arresters must be chosen, such that at the terminals of the transformer bushings a lightning overvoltage of $1425 \text{ kV} / 1.15 = 1239 \text{ kV}$ is not exceeded. See IEC 60071-1 and 60071-2 for exact definitions of the terms men-

tioned and how they are determined and applied during the insulation coordination procedure.

SCD: → [specific creepage distance](#)

Section of an arrester: a complete, suitably assembled part of an arrester which reproduces the behavior of the complete arrester with respect to a particular test. A section of an arrester is not necessarily a → [unit of an arrester](#) (IEC 60099-4, 3.5). An example for the section of an arrester is the → [thermally equivalent prorated section](#).

Separation distance: → [protective zone of an arrester](#)

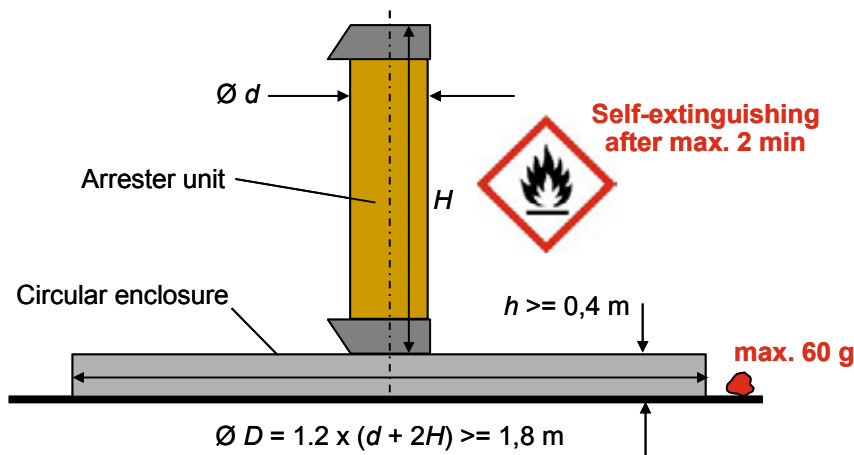
Short-circuit current strength: → [Short-circuit withstand \(capability\)](#)

Short-circuit rating: → [Short-circuit withstand \(capability\)](#)

Short-circuit tests: (previously: pressure-relief tests) on arresters, for which the manufacturer claims a → [short-circuit withstand capability](#), these tests prove, among other things, that the arrester housing is able to withstand short-circuit currents under specified test conditions without causing violent shattering of the housing (an unpressurized, non-explosive breaking is explicitly permitted). Testing must be carried out with the → [rated short-circuit \(withstand\) current](#) I_s (duration of current flow 200 ms) and with two reduced short-circuit currents (duration also 200 ms) (approx. 50% and approx. 25% of I_s), and with one low short-circuit current of 600 A \pm 200 A (duration 1 s). The standardized currents are summarized in the table. For the high (rated and reduced) currents, the test is performed on the longest unit of a type. The unit length for the low current is not specified. In arresters with an enclosed gas volume, the short-circuit is then

Rated short-circuit current (duration 200 ms) / A	Reduced short-circuit currents (duration 200 ms) / A		Low short-circuit current (duration 1 s) / A
80 000	50 000	25 000	600 \pm 200
63 000 ¹	25 000	12 000	
50 000	25 000	12 000	
40 000	25 000	12 000	
31 500	12 000	6 000	
20 000	12 000	6 000	
16 000	6 000	3 000	
10 000	6 000	3 000	
5 000	3 000	1 500	

initiated with an ignition wire and otherwise with a deliberate overload of the active part by applying a high voltage (in fact the difference between the arrester types for the short-circuit test is more complicated, see IEC 60099-4). In the first case, the current is overlaid with a decaying DC component, to reach the first peak value of 2.5 times the root-mean-square value (i.e., where $I_{\text{rms}} = 80 \text{ kA}$: $i = 200 \text{ kA}$). The test is passed if no parts weighing more than 60 g are found outside the (usually circular) area, as shown in the figure. It is also a requirement that any open fire that occurs extinguishes itself within two minutes.



Short-circuit withstand (capability): ability of an arrester to withstand the short-circuit current that flows after an overload, without causing violent shattering of the housing. The short-circuit withstand capability used to be referred to as → [pressure relief class](#), and is now indicated as → [rated short-circuit \(withstand\) current](#) and proved by means of → [short-circuit tests](#), or pressure relief tests.

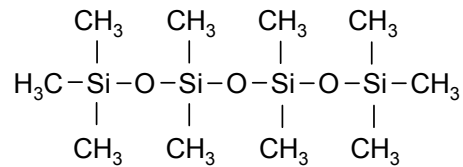
SiC resistor: → [Silicon-carbide resistor](#)

SILHH: abbreviation for "basic switching impulse insulation level". Even though this term is frequently used when referring to → [IEC](#) standards, it is only defined by → [IEEE](#) and → [ANSI](#) (see standards IEEE Std 1313.1-1996, IEEE Std C62.2-1987, IEEE Std C62.22-1997, ANSI C92.1-1982). The IEC standard 60071-1, Seventh edition, 1993-12, uses the term → [standard rated switching impulse withstand voltage](#) → [SIWV](#) instead.

Silicon-carbide resistor: (SiC resistor) non-linear resistor, which was used in the arresters before the introduction of → [metal-oxide resistors](#). The non-linearity of its → [voltage-current-characteristic](#) is considerably less pronounced than in a metal-oxide resistor. Thus arresters with silicon-carbide resistors need serial spark gaps, which separate the arrester from the line during continuous operation, and which interrupt the

power-frequency follow current that flows through the arrester after a discharge operation.

Silicone rubber: (correct chemical short form: SI, or, depending on the particular type: MQ, VMQ, PMQ, PVMQ; in the literature frequently: SIR). The basic Si-O-Si-O structure with its attached methyl groups (CH₃) is characteristic of silicone rubber:



Fillers, such as aluminum trihydrate (ATH) or special additives, affect the tracking and erosion resistance which is needed in high-voltage applications. Not only does silicone rubber provide such important advantages as high elasticity and tear resistance, high temperature resistance (trouble-free application within the temperature range of $-45\text{ }^{\circ}\text{C}$ to $+180\text{ }^{\circ}\text{C}$), flame retardant properties (if burning does occur, only silica acid remains) and high electric field strength, but also the most notable property of silicone rubber, its [→hydrophobicity](#): water simply drips off the silicone surface. This property also transfers to pollution layer films, in that the silicone rubber insulator is water repellent even in heavily polluted conditions, and thus lends the associated devices especially good operating characteristics in polluted environments. The hydrophobicity can indeed decrease when exposed to the long-term effects of moisture or to electric discharge activities; however, after these conditions discontinue, the original water-repellent properties return within a short time (in a few hours or days) – a mechanism, whose effect, as far as is presently known, is interminable. Silicone rubber is processed into three different basic forms: [→HTV silicone rubber](#), [→RTV silicone rubber](#) and [→LSR or LR](#).

Single impulse energy handling capability: the maximum absorbable energy of an arrester during a single discharge operation. Besides some other influencing factors, it is mainly limited by the maximum allowable thermo-mechanical stress on the ceramic of the MO resistors. If this energy value is exceeded thermo-mechanical breaking, puncturing, or flashover of the MO resistors may occur (see picture). The single impulse



energy handling capability is smaller than the →[thermal energy handling capability](#). Both energies, however, are not stated as such in the IEC standards, and thus are not specified by every manufacturer; and if they are, then frequently under different and incomparable basic conditions. →[Long duration current impulse withstand capability](#) can be considered to be an indirect measure of the single impulse energy handling capability. According to IEC 60099-4, however, the energy handling capability can only be defined by the →[line discharge class](#).

SIR: →[Silicone rubber](#)

SIWV: abbreviation for "[standard rated switching impulse withstand voltage](#)" as specified in IEC 60071-1. Equivalent to →[SIL](#) in the American IEEE standards.

SLL: specified long-term load. It is defined in IEC 60099-4 as a force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for long periods without causing any mechanical damage to the arrester. Compare →[SSL](#). See also →[mechanical loads](#).

Slow-front overvoltageHH: transient overvoltage, normally unidirectional, with times to peak of 20 µs up to 5000 µs and →[times to half-value on the tail](#) of not more than 20 ms (IEC 60071-1, 3.17).

Solidly earthed neutral system: a system within which one or more transformer neutral points are directly connected to the earth (IEC 60071-1, 3.12).

Specific creepage distance: (SCD) →[creepage distance](#) of an insulator in relation to the →[highest voltage for the equipment](#), U_m (phase-to-phase voltage!), given in mm/kV. For example, an insulator with a creepage distance of 10 500 mm for use in a 420-kV-system has a specific creepage distance of 25 mm/kV. IEC 60815, Ed. 1 of 1986 referred to the specific creepage distance. The new series IEC60815-1, -2 and -3, which was published in 2008, defines and uses the →[unified specific creepage distance](#), which uses the phase-to-earth voltage instead of the phase-to-phase voltage. According to this definition the example arrester has a *unified* specific creepage distance of 43.3 mm/kV. The specific creepage distance is selected on the basis of the relevant →[pollution level](#).

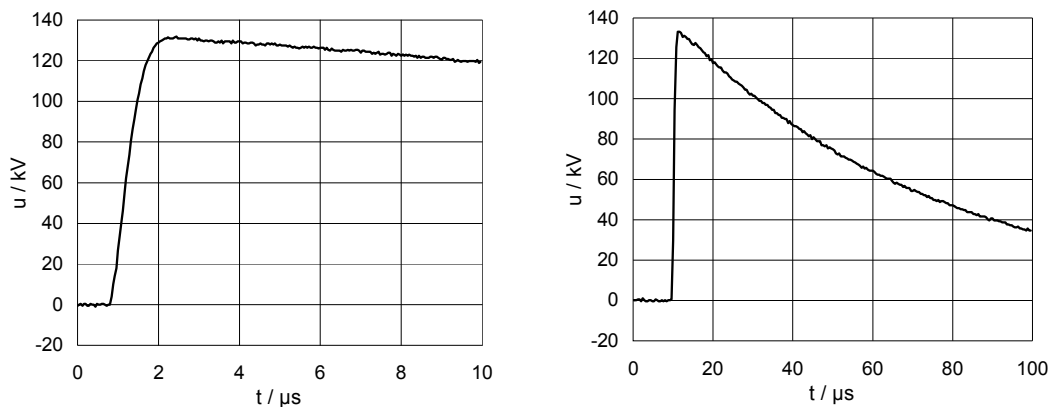
Specified long-term load: →[SLL](#).

Specified short-term load: →[SSL](#).

SSL: specified short-term load. It is defined in IEC 60099-4 as a force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for short peri-

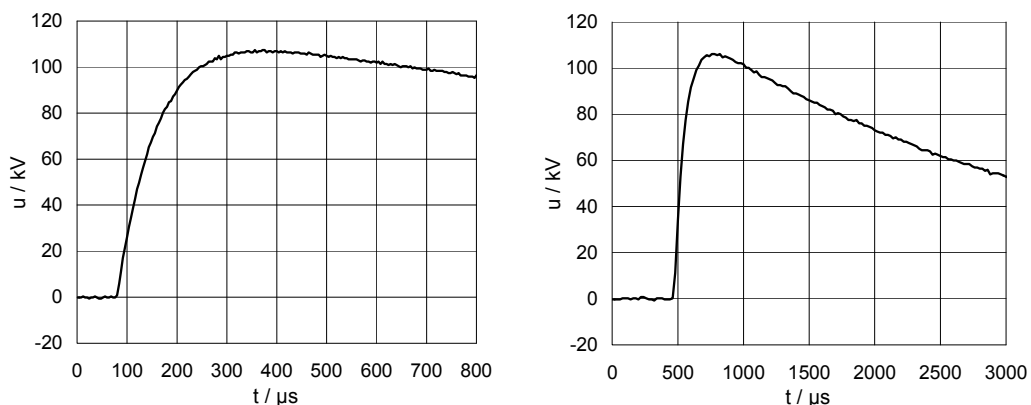
ods and for relatively rare events (for example, short-circuit current loads, very high wind loads or seismic loads) without causing any mechanical damage to the arrester. For seismic loads an even higher load than the SSL may be considered. Compare →[SLL](#). See also →[mechanical loads](#).

Standard lightning impulse (voltage): a standard test voltage defined in IEC 60060-1, used to prove that the insulation can withstand the stress imposed by →[fast-front overvoltages](#). The standard lightning impulse 1.2/50 has a front time of 1.2 μs and a →[time to half-value on the tail](#) of 50 μs . The following two oscillograms show the standard lightning impulse in two different time resolutions.



Standard rated lightning impulse withstand voltage: (→[LIWV](#) also known in American standards as →[BIL](#) for "basic lightning impulse insulation level") a standard value of a [lightning impulse test voltage](#), which is used in a standard withstand test to prove that the insulation complies with the required withstand voltage. The different standard lightning impulse withstand voltage values associated with the →[highest voltage for equipment, \$U_m\$](#) , are found in IEC 60071-1, Tables 2 and 3.

Standard switching impulse (voltage): a standard test voltage defined in IEC 60060-1 used to prove that the insulation can withstand the stress imposed by →[slow-front overvoltages](#). The standard switching impulse 250/2500 has a front time of 250 μs and a

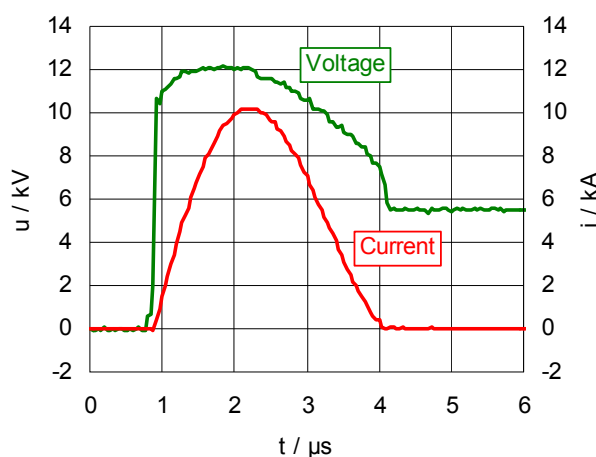


→[time to half-value on the tail](#) of 2500 μs . The two oscillograms show the standard switching impulse in two different time resolutions.

Standard rated switching impulse withstand voltage: (→[SIWV](#): also known in American standards as →[SIL](#) for "basic switching impulse insulation level") a standard value of a switching impulse test voltage, which is used in a standard withstand test to prove that the insulation complies with the required withstand voltage. According to IEC 60071-1, standard switching impulse withstand voltages are only specified for →[range II](#), that is voltage levels of $U_m > 245 \text{ kV}$. The different standard switching impulse withstand voltage values associated with the →[highest voltage for equipment, \$U_m\$](#) , are found in IEC 60071-1, Table 3.

Standard withstand voltage: (symbol: U_w) a term from the →[insulation coordination](#): the standard value of the test voltage applied in a standard withstand test. For an exact definition of the term and its meaning and determination during the process of insulation coordination, see IEC 60071-1 and 60071-2. Also see →[safety factor \$K_s\$](#) .

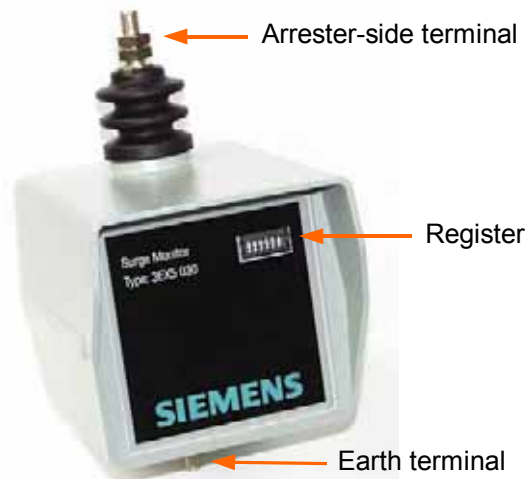
Steep current impulse: →[current impulse](#) with a →[front time](#) between 0.9 μs and 1.1 μs and a →[time to half-value on the tail](#) of not more than 20 μs (IEC 60099-4, 3.16). Steep current impulses are used in the laboratory to ascertain the →[voltage-current-characteristic](#) of arresters, →[arrester sections](#) or →[MO resistors](#). They are produced in a low-inductance, frequently coaxial test setup by a practically undamped capacitor discharge into the test sample. The current amplitudes are within a range of 1.5 kA to 20 kA. The following oscillogram depicts an example of a residual voltage measurement on an MO resistor at a steep current impulse of 10 kA:



Steep current impulse protective level: maximum value of the →[residual voltage](#) of an arrester at a →[steep current impulse](#) of the same peak value as the →[nominal discharge current](#).

Sulfur cement: a type of cement which, for example, is used to cement metal flanges on porcelain insulators. Sulfur cement consists of about 65% highly pure sulfur and about 35% mineral fillers. It is poured at temperatures of about 140 °C and begins to set when the temperature falls below 120 °C. The advantage of sulfur cement over → [Portland cement](#), is, among others, its trouble-free contact with aluminum. The disadvantage is the loss of strength which begins to occur at temperatures above 90 °C. Since these temperatures are not achieved in arrester flanges, sulfur cement is frequently used for arresters.

Surge counter: a device externally fixed to the arrester (see picture below), which has an electromechanical or electronic register to record the number of arrester operations. The surge counter is series-connected with the arrester in its earth connection. This requires installation of the arrester isolated from the ground by means of insulating feet. See also → [Leakage current indicator](#).



Surge impedance: impedance relevant for traveling wave processes on a line. Ignoring the resistive components (i.e. assuming a lossless line), the surge impedance results

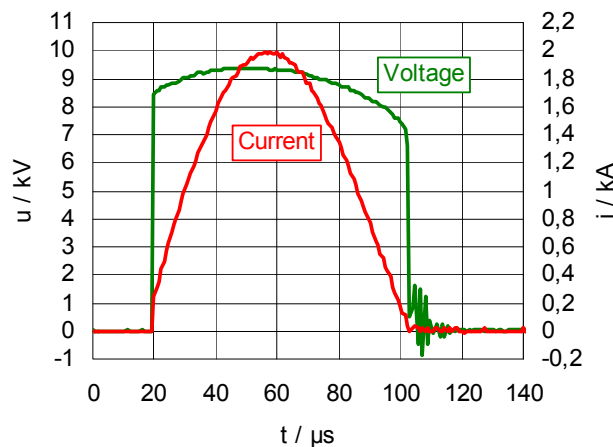
$$Z = \sqrt{\frac{L'}{C'}}$$

from the inductance and the capacitance per unit length of the line as:

with	Z	surge impedance in Ω
	L'	inductance per unit length in H/m
	C'	capacitance per unit length in F/m

From the equation above it is clear that the surge impedance is not dependent upon the length, that is, it is the same on every location on the line. For high-voltage transmission lines its value is between about $300\ \Omega$ ($U_s = 800\text{ kV}$) and $450\ \Omega$ ($U_s \leq 245\text{ kV}$) (see IEC 60099-1, Table C.1).

Switching current impulse: peak value of a [current impulse](#) with a [front time](#) of between $30\ \mu\text{s}$ and $100\ \mu\text{s}$ and a [time to half-value on the tail](#) of roughly double the front time (IEC 60099-4, 3.32). Switching current impulses are used in the laboratory to ascertain the [voltage-current-characteristic](#) of arresters, [arrester sections](#) or [MO resistors](#). They are produced by a capacitor discharge in an aperiodically damped RLC circuit. The current amplitudes are within a range of 125 A to 2 kA (see IEC 60099-4, Table 4). The oscillogram depicts an example of a residual voltage measurement on an MO resistor at a switching current impulse of 2 kA :

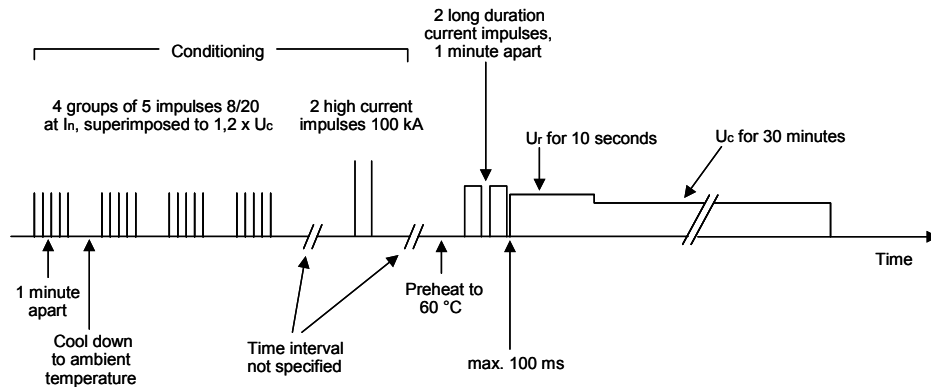


Switching impulse protective level: maximum value of an arrester's [residual voltage](#) at standard [switching current impulses](#). It is listed in each case for two different current impulse peak values within the range of 125 A to 2000 A (IEC 60099-4, Table 4).

Switching impulse residual voltage: [residual voltage](#) of the arrester at [switching current impulse](#). The switching current impulse peak values are found in IEC 60099-4, 8.3.3, Table 4.

Switching overvoltage: transient overvoltage caused by transient phenomena as a result of switching operations or system failures (earth faults, inductive or capacitive switching, load rejection, ferroresonance, etc.). The frequency is within a range of 100 Hz to 10 kHz , and front times occur in the order of magnitude of $30\ \mu\text{s}$ to $3000\ \mu\text{s}$. The voltage amplitudes can take on between 2 p.u. and 3 p.u. ($1\text{ p.u.} = \sqrt{2} \cdot U_s / \sqrt{3}$), depending on the system voltage. Switching overvoltages usually belong to the class of [slow-front overvoltages](#), according to IEC 60071-1.

Switching surge operating duty test^{HH}: see IEC 60099-4, 8.5.5. To be carried out on 10-kA-arresters of →[line discharge classes](#) 2 and 3, as well as on 20-kA-arresters of line discharge classes 4 and 5. The sequence is schematically depicted in the following diagram:



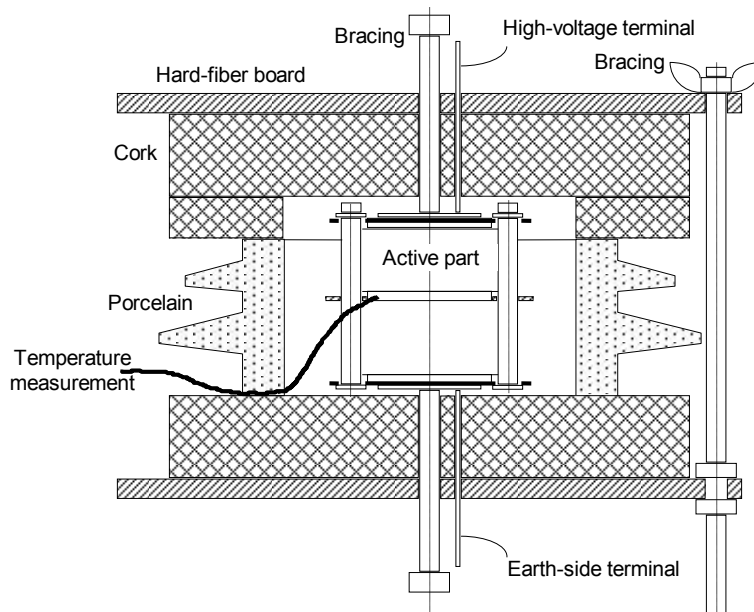
Temporary overvoltage: (abbreviation: TOV) power-frequency overvoltage which can occur for a duration of several tenths of a second to up to a few seconds, as a result of a switching operation or system failure. Its value depends on the type of →[neutral earthing](#) in the system. A special case would involve →[resonant earthed](#) and →[isolated neutral](#) systems, in which the phase-to-earth voltage of the healthy phases takes on the value of the phase-to-phase voltage, in case of an earth fault. This operating condition can last for a long time (up to several hours).

Tests: →[Type tests](#), →[Routine tests](#), →[Acceptance tests](#)

Thermal energy handling capability: maximum amount of energy that can be absorbed by an arrester in the form of several subsequent discharges within a short time interval, without leading to →[thermal instability](#) (see also [Figure 7](#)). The thermal energy handling capability is greater than the →[single impulse energy handling capability](#). Both energies, however, are not stated as such in the IEC standards, and thus are not specified by every manufacturer; and if they are, then frequently under different and incomparable basic conditions. It makes sense to refer to the →[switching surge operating duty test](#) in this context; in that case the thermal energy handling capability would be the maximum energy which can be injected into the arrester in the form of two →[long duration current impulses](#), by the procedure, under the conditions and according to the pass criteria of the operating duty test. According to IEC 60099-4, the energy handling capability is only defined by the →[line discharge class](#).

Thermally equivalent prorated section: (also known as "thermal equivalent") a →[section of an arrester](#) used in the →[operating duty test](#), which reproduces the electri-

cal as well as the thermal behavior of a complete arrester. The requirements on this section are found in IEC 60099-4, 8.5.3.2 (which is nevertheless contradictory in places). In principle, a thermally equivalent prorated section is a cutout of the original arrester, whose terminals are so well thermally insulated that the heat is mostly dissipated radially (as it is the case with the real arrester). The picture shows an example which represents a porcelain housed high-voltage arrester.



Thermal instability: the (unstable) operating condition of an arrester, which has been heated beyond its → [thermal stability limit](#) (refer to [Figure 7](#)) by injecting impermissibly high energy, while being connected to power-frequency voltage. If it is not disconnected quickly enough, the arrester heats itself up because of the greatly increased leakage current, until it self-destroys (also known as "thermal runaway").

Thermal model of an arrester: → [Thermally equivalent prorated section](#)

Thermal runaway: → [Thermal instability](#)

Thermal stability limit: highest temperature of the MO resistors, at which an arrester at applied power-frequency voltage and at the highest ambient temperature of $+40\text{ }^{\circ}\text{C}$, as defined by the → [normal service conditions](#), can still cool down to its normal operating temperature. Also see [Figure 7](#) with the accompanying explanation. The values of the thermal stability limit, depending on the actual arrester design, are in the range of $190\text{ }^{\circ}\text{C}$ to about $220\text{ }^{\circ}\text{C}$.

TLA: → [Line arrester](#)

TLSA: → [Line arrester](#)

TOV: → [Temporary overvoltage](#)

Transmission line (surge) arrester: → [Line arrester](#)

Traveling waves: Voltage and current impulses spread as traveling waves on the line when their rise time or their overall duration of appearance is shorter than the propagation time of an electromagnetic wave on a line (which under this condition is called an "electrically long line"). They always occur in fast-front overvoltages (principal cause: lightning overvoltages), but almost never in slow-front overvoltages (principal cause: switching overvoltages). The amplitudes of the voltage and current waves in this case are linked to each other by the → [surge impedance](#) Z of the line ($U = Z \cdot I$). According to the rules of traveling wave processes, refraction and reflection occur where the surge impedance of the line changes. For example if a line with surge impedance Z_1 meets another line with surge impedance Z_2 or a terminating resistor with (real-valued) impedance Z_2 , the voltage refraction factor is $\beta_u = 2 \cdot Z_2 / (Z_2 + Z_1)$ and the voltage reflection factor is $r_u = (Z_2 - Z_1) / (Z_2 + Z_1)$. This especially can lead to voltage amplitude and voltage steepness increases (in extreme cases, up to double the amount) and is to be taken into account when determining the protective level of an arrester and its location (→ [protective zone of an arrester](#)).

Type tests: According to IEC 60099-4, MO arresters without gaps are to be subjected to the following type tests:

- Insulation withstand tests on the housing
- → [Residual voltage](#) tests
- → [Long duration current impulse withstand test](#)
- → [Operating duty test](#)
- → [Short-circuit tests](#)
- Artificial pollution test (in accordance with Annex F of IEC 60099-4)
- Tightness test (sealing test)
- Current sharing test (only in the case of multi-column arresters)
- Mechanical tests

U_c : → [Continuous operating voltage of an arrester](#)

U - I -characteristic: → [Voltage-current-characteristic](#)

U_m : → [Highest voltage for equipment](#)

U_n : → [Nominal voltage of a system](#)

Unified specific creepage distance: (USCD) → [creepage distance](#) of an insulator in relation to the value of the highest system operation voltage at the insulator (in other words → the [highest voltage for equipment](#)) divided by the square root of three ($U_m/\sqrt{3}$), and given in mm/kV. For example, an insulator with a creepage distance of 10 500 mm for use in a 420-kV-system has a unified specific creepage distance of 43.3 mm/kV. IEC 60815, Ed. 1 of 1986 still referred to the → [specific creepage distance](#), which uses the phase-to-phase voltage as the reference value and therefore differs from the unified specific creepage value by a factor of $\sqrt{3}$. The new series IEC60815-1, -2 and -3 introduced the unified specific creepage distance in 2008. The specific creepage distance is selected on the basis of the relevant → [pollution level](#).

Unit of an arrester: a completely housed part of an arrester which may be connected in series and/or in parallel with other units to construct an arrester of higher → [rated voltage](#) and/or current rating (IEC 60099-4, 3.6).

U_r : → [Rated voltage of an arrester](#)

U_{ref} : → [Reference voltage](#)

U_{rw} : → [Required withstand voltage](#)

U_s : → [Highest voltage of a system](#)

USCD: → [Unified specific creepage distance](#)

U - t -characteristic: → [Power-frequency voltage versus time characteristic](#)

U_w : → [Standard withstand voltage](#)

Vacuum-impregnated FRP tube: implementation of an → [FRP](#) tube which is manufactured by impregnating the previously wound dry fiber-glass construction in resin, under vacuum conditions. By using this manufacturing process, total absence of voids can be achieved (thus eliminating the risk of internal partial discharges and related deterioration effects, even under highest electric fields stress conditions), as well as high bending strength, when the glass fibers are mostly orientated in axial direction, which is not possible with the → [wet-process](#). This type of manufacturing is, however, more expensive than the wet-process.

Very-fast-front overvoltage: transient overvoltage, normally unidirectional, with time to peak not greater than $0.1\ \mu\text{s}$, a total duration below 3 ms, and with superimposed oscillations at a frequency between 30 kHz and 100 MHz (IEC 60071-1, 3.17).

V - I -characteristic: → [Voltage-current-characteristic](#)

Virtual front time of a current impulse (T_1): the time in microseconds equal to 1.25 the time in microseconds for the current to increase from 10% to 90% of its peak value (IEC 60099-4, 3.23).

Virtual time to half-value on the tail of an impulse (T_2): the time interval between the virtual origin of the impulse and the instant in which the voltage or the current has decreased to half of its peak value; expressed in microseconds (IEC 60099-4, 3.25).

Voltage-current-characteristic: (also: U - I -characteristic or V - I -characteristic) representation of the dependency of arrester voltage on current. Usually the voltage peak values are on the ordinate, frequently with per unit values related to the → [lightning impulse protective level](#). The current peak values (resistive component only) are on the abscissa, represented logarithmically and within a range of several decades of magnitude (e.g. from $10\ \mu\text{A}$ to 100 kA). See [Figure 2](#) for an example of a voltage-current characteristic.

V - t -characteristic: → [Power-frequency voltage versus time characteristic](#)

Vulcanization: cross-linking of the individual molecule chains of a polymer material to a three-dimensional network. The cross-linked material is often designated with an additional "XL". Example: the thermoplastic polyethylene (PE) becomes thermo-elastic cross-linked polyethylene (XLPE).

Wet-processed FRP tube: → [FRP](#) tube, which is manufactured by winding up resin impregnated fiber-glass rovings on a core. This production process requires that the glass fibers can only be set up diagonally (thus, for example, not exactly in the direction of the core axis, as is possible with → [vacuum-impregnated FRP tubes](#)). As a result the achievable bending strength usually remains below that of a similarly dimensioned vacuum-impregnated tube when the direction of the glass fibers is mostly in axial direction. In addition, voids cannot totally be avoided; these can cause dielectric and ageing problems under extremely high electric field stress in service (risk of internal partial discharges; however, the critical electric field stress is never achieved when the FRP tubes are used for the composite housings of outdoor arresters). Wet-processed tubes are easier to manufacture than vacuum-impregnated tubes.

Withstand voltage: the value of the test voltage to be applied under specified conditions in a withstand test, during which a specified number of disruptive discharges is tolerated (IEC 60071-1, 3.23; see there also for additional details).

ZnO resistor: → [MO resistor](#)

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