# IEC TR 60099-10

Edition 1.0 2024-06

# TECHNICAL REPORT

colour inside

## Surge arresters –
## Part 10: Rationale for tests specified by IEC 60099-4:2014



IEC TR 60099-10:2024-06(en)

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INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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# SURGE ARRESTERS –

## Part 10: Rationale for tests specified by IEC 60099-4:2014

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IEC TR 60099-10 has been prepared by IEC technical committee 37: Surge arresters. It is a Technical Report.

The text of this Technical Report is based on the following documents:

| Draft | Report on voting |
|---|---|
| 37/XX/DTR | 37/XX/RVDTR |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 60099 series, published under the general title *Surge arresters*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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# INTRODUCTION

This part of IEC 60099, which is a Technical Report, is informative in nature and does not contain requirements. Its primary purpose is to provide information to users of IEC 60099-4 to help them understand the underlying rationale for the tests and the specified test parameters.

A secondary purpose is to keep a record of substantive changes in the rationale over the last few editions of the standard.

This first edition of the Technical Report covers the tests specified in IEC 60099-4:2014. As tests are added, modified or deleted in future editions of IEC 60099-4, it is planned to amend this Technical Report to reflect such changes. It is understood that rationale behind requirements may change significantly over time, for example when a whole new test philosophy is implemented in a standard.

# SURGE ARRESTERS –

# Part 10: Rationale for tests specified by IEC 60099-4:2014

## 1 Scope

This part of IEC 60099, which is a Technical Report, is applicable to all tests and arrester types included in IEC 60099-4:2014 and explains the rationale behind each test specified in that document.

This document does not contain requirements and is not intended to replace any clauses of IEC 60099-4:2014.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60099-4:2014, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60099-4:2014 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

## 4 Structure of the document

### 4.1 Content of each individual test rationale

Each test rationale clause (see Clauses 5 to 21), with the exception of the routine and acceptance test rationales (see Clause 22), is structured as follows (with X representing the clause number):

- X.1 Arrester types for which the test is applicable
- X.2 Purpose of the test
- X.3 Historical notes
- X.4 Test rationale
  - X.4.1 General
  - X.4.2 Sample selection rationale
  - X.4.3 Test procedure rationale
  - X.4.4 Evaluation rationale
  - X.4.5 Common misunderstandings (applicable only to Clauses 5, 8, 10, 11 and 13)

Historical notes provide information with regard to the known first use in IEC 60099-4, initial references used to develop the test, and major changes over time.

The "Common misunderstandings" subclauses provide general comments with regard to often misunderstood uses of the characteristics being verified in IEC 60099-4:2014.

## 4.2 Relation between each test of IEC 60099-4:2014 and this document

All arrester types covered by IEC 60099-4:2014 are covered in this document. A rationale is provided for each test in IEC 60099-4:2014, including the routine and acceptance tests, with the following exceptions because these tests are under consideration by IEC Technical Committee 37 at the moment of publication of this technical report:

- the insulation withstand tests for GIS arresters and separable and dead-front arresters (IEC 60099-10:2014, 11.8.2 and 12.8.2).
- the short-circuit tests for separable and dead-front and liquid-immersed arresters (IEC 60099-10:2014, 12.8.10 and 13.8.10).
- the test after erection on site for GIS arresters (IEC 60099-4:2014, 11.10).
- the internal partial discharge test for separable and dead-front arresters (IEC 60099-4:2014, 12.8.17).

Table 1 shows which clause/subclause of this document applies to each test of IEC 60099-4:2014, for each arrester type.

**Table 1 – Test rationale clause/subclause number for each test in 60099-4:2014**

<table>
<tr><th colspan="2">Tests in 60099-4:2014</th><th colspan="5">Test rationale clause/subclause number in this document for each arrester type</th></tr>
<tr><th>Clause/subclause number[a]</th><th>Title</th><th>Porcelain housed</th><th>Polymer housed</th><th>Gas insulated metal-enclosed</th><th>Separable and dead-front</th><th>Liquid immersed</th></tr>
<tr><td>8.2</td><td>Insulation withstand tests</td><td colspan="2">5</td><td colspan="2">Not included in this edition</td><td>5</td></tr>
<tr><td>8.3</td><td>Residual voltage tests</td><td colspan="5">6</td></tr>
<tr><td>8.4</td><td>Test to verify long term stability under continuous operating voltage</td><td colspan="5">7</td></tr>
<tr><td>8.5</td><td>Test to verify the repetitive charge transfer rating, $Q_{rs}$</td><td colspan="5">8</td></tr>
<tr><td>8.6</td><td>Heat dissipation behavior of test sample</td><td colspan="5">9</td></tr>
<tr><td>8.7</td><td>Operating duty test</td><td colspan="5">10</td></tr>
<tr><td>8.8</td><td>Power-frequency voltage-versus-time test</td><td colspan="5">11</td></tr>
<tr><td>8.9</td><td>Test of arrester disconnector</td><td colspan="2">12</td><td colspan="3">N/A</td></tr>
<tr><td>8.10</td><td>Short-circuit tests</td><td colspan="3">13</td><td colspan="2">Not included in this edition</td></tr>
<tr><td>8.11</td><td>Test of the bending moment</td><td>14</td><td>15</td><td colspan="3">N/A</td></tr>
<tr><td>8.12</td><td>Environmental tests</td><td>16</td><td colspan="4">N/A</td></tr>
<tr><td>8.13</td><td>Seal leak rate test</td><td colspan="2">17</td><td colspan="3">N/A</td></tr>
</table>

| Tests in 60099-4:2014 | | Test rationale clause/subclause number in this document for each arrester type | | | | |
|---|---|---|---|---|---|---|
| **Clause/subclause number[a]** | **Title** | **Porcelain housed** | **Polymer housed** | **Gas insulated metal-enclosed** | **Separable and dead-front** | **Liquid immersed** |
| 8.14 | Radio interference (RIV) test | 18 | | | | |
| 8.15 | Test to verify the dielectric withstand of internal components | 19 | | | | |
| 8.16 | Test of internal grading components | 20 | | | | |
| 10.8.17 | Weather aging test | N/A | 21 | N/A | | |
| 9 | Routine tests and acceptance tests | 22 | | | | |

[a] For subclause numbers starting with 8 (ex.: 8.2), equivalent subclauses in Clauses 10, 11, 12 and 13 are also included (e.g. 10.8.2, 11.8.2, 12.8.2 and 13.8.2 are included in the same line as per 8.2)

# 5 Insulation withstand tests rationale

## 5.1 Arrester type for which the tests are applicable

Insulation withstand tests apply to all types of arresters. This clause includes the test rationales for porcelain-housed arresters, polymer-housed arresters and liquid-immersed arresters only. Specificities applicable to GIS arresters and separable and dead-front arresters are under consideration in IEC Technical Committee 37 and are not included yet herein.

However, if an arrester has a dry arc distance longer than the specified levels in IEC 60099-4:2014, they are exempt from this test. Also, the switching impulse withstand test is required for arresters applied to systems with $U_s$ > 245 kV only.

## 5.2 Purpose of the tests

The voltage withstand tests demonstrate the voltage withstand capability of the external insulation of arrester housings.

## 5.3 Historical notes

These tests were added for the first time in IEC 60099-4:1991. There was no reference to this type of test in IEC 60099-1.

Historically, tests on individual housings only were specified irrespective of arrester rating and tests on complete housing assemblies were "under consideration". This was changed in IEC 60099-4:2014 to require tests on arresters for systems with $U_s$ > 245 kV to be performed using complete housing assemblies including the external grading systems. For systems with $U_s \leq$ 245kV, tests are still permitted on individual unit housings.

## 5.4 Tests rationale

### 5.4.1 General

This test is a procedure to verify that the housing will not experience an external flashover under anticipated transient conditions that may occur over the life of the arrester. This is not a lightning impulse withstand (LIWV) test, a switching impulse withstand voltage (SIWV) nor a power frequency voltage (PFWV) test as applied to other high voltage equipment.

Arresters are unique in that they are self-protecting devices which means that the internal nonlinear resistors of the arrester will inherently limit the voltage across the terminals. Due to this self-protecting nature, the arrester housing can have lower withstand voltages than the rest of the system without any negative impact on the system withstand level.

There are three types of insulation withstand voltages used in this test, intended to represent the three types of overvoltage stresses that an arrester will experience in its lifetime, namely lightning, switching and power frequency.

The general rationale for the insulation withstand tests on liquid-immersed arresters is the same as for porcelain-housed and polymer-housed arresters. Nevertheless, because these arresters are operated while immersed in liquid, all tests have to be performed in this same liquid and everything related to other ambient conditions must be ignored: no wet tests, no type test exceptions because of dry arc to test voltage relation, no correction factor to take into account density and humidity, etc. The liquid temperature is presumed to have no major impact on its insulation withstand. So, room temperature is accepted for this test, as it is the case for power transformers.

### 5.4.2 Sample selection rationale

#### 5.4.2.1 Rationale applicable to all withstand tests

When individual arrester unit housings are tested, it is expected that the housing design under test shall be the one that is stressed at its maximum level. The test is thus to be made on the longest unit and on the most stressed unit (these may be two different units depending on the arrester design). In determining the most stressed unit, the complete arrester assembly must be considered, including any type of additional external or internal grading (for example grading rings or internal capacitors).

For an arrester intended for application on a system where $U_s$ > 245 kV, the complete arrester housing assembly has to be tested, including internal means to achieve as close as possible the grading that would be present under high current discharges in the actual arrester.

In all cases, where the standard does not require internal grading, it is acknowledged that the removal of the active components will affect the results, but this practice has been used for many years to evaluate arrester housing impulse withstand capability.

#### 5.4.2.2 Rationale specific to the lightning impulse test

The lightning impulse withstand capability of an air gap is a linear function of distance with an electric field of 500 kV/m. Therefore, a test is not required if the dry arcing distance or the sum of the partial dry arcing distances in m is larger than the test voltage in kV divided by 500 kV/m. Figure 1, from CIGRÉ TB 696-2017, presents the combination of different path (dry arcing distances) to consider from the high voltage side of the arrester to the ground.

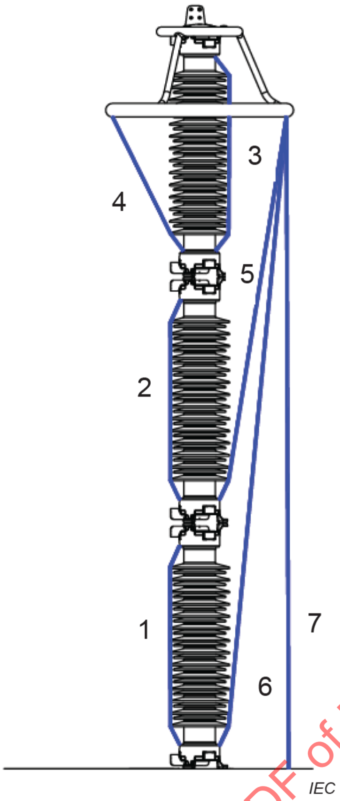



**Figure 1 – Possible arcing distances (7 paths to consider for this example) for a multi-unit arrester (from CIGRÉ 696-2017)**



#### 5.4.2.3 Rationale specific to the switching impulse test

The test is to be performed on a complete arrester assembly due to the fact that the switching withstand voltage is a nonlinear function of the dry arc distance and mitigating factors such as the grading rings make an estimate for multiple sections inaccurate.

For samples intended to be used indoor, it is acceptable to complete this test in dry conditions. For samples intended to be used outdoor, the arrester must be tested in wet conditions. Both of these scenarios represent real world applications.

If an arrester has a dry arcing distance or a sum of partial dry arcing distances (see Figure 1) that exceed the minimum requirement calculated with the following formula, this test is not required:

$$d = 2{,}2 \times \left[ e^{(U/1069)} - 1 \right] \tag{1}$$

where:

$d$ is the distance, in m.

$U$ is the test voltage, in kV.

The equation in IEC 60099-4:2014, 8.2.7 gives the limit which comes from IEC 60071-2:1996, Annex G "*Calculation of air gap breakdown strength from experimental data*". The equation is derived from formula G.3 of this latter standard, where $U_{50}$ is given as:

$$U_{50} = k \times 1080 \times \ln(0{,}46 \times d + 1) \quad (2)$$

where:

$k$ is the gap factor.

$d$ is the distance, in m.

For the purpose of IEC 60099-4:2014, the gap factor $k$ is assumed to be equal to 1,1 and two standard deviations of 0,05 each are taken into account to achieve the withstand voltage.

#### 5.4.2.4 Rationale specific to power-frequency voltage test

Since this test is only required on arresters applied to systems where $U_s$ ≤ 245 kV, the testing need only be made on individual unit housings.

For samples intended to be used indoor, it is acceptable to complete this test in dry conditions. For samples intended to be used outdoor, the arrester must be tested in wet conditions. Both of these scenarios represent typical applications.

If an arrester has dry arcing distances that exceed minimum requirements this test can be excluded. The equation in IEC 60099-4:2014, 8.2.8 gives the limit which comes from IEC 60071-2:1996, Annex G "*Calculation of air gap breakdown strength from experimental data*". The equation is derived from formula G.1, where the peak value of $U_{50}$ is given as:

$$U_{50} = 750 \times \sqrt{2} \times \ln\left(1 + 0{,}55 \times d^{1{,}2}\right) \quad (3)$$

where:

$d$ is the distance, in m.

Following the recommendations given in IEC 60071-2:1996, for the purpose of IEC 60099-4:2014, the gap factor $k$ is assumed to be equal to 1, the withstand voltage is assumed to be 90 % of $U_{50}$, and a 10 % reduction in $U_{50}$ is assumed for wet conditions compared to dry.

### 5.4.3 Test procedure rationale

#### 5.4.3.1 Rationale specific to the lightning impulse voltage test

In this test, the minimum withstand voltage must be 1,3 times the residual voltage at nominal discharge current. This elevation correction factor for an altitude (H) of 1 000 meters is obtained from the following formula:

$$U = 1{,}15 \times e^{(1000/8150)} \quad (4)$$

where:

$U$ is the test voltage, in kV.

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

The test is specified to be conducted in dry conditions since rain and humidity have little effect on the results of the test.

#### 5.4.3.2 Rationale specific to the switching impulse voltage test

The switching impulse voltage test is used to verify the specified slow front withstand voltages for arresters applied to systems with $U_s$ > 245 kV, because the 250/2 500 µs wave shape results in the lowest withstand capability of an insulator in Range 2 system voltages, as shown in Figure 2 (ranges defined in IEC 60071-1).

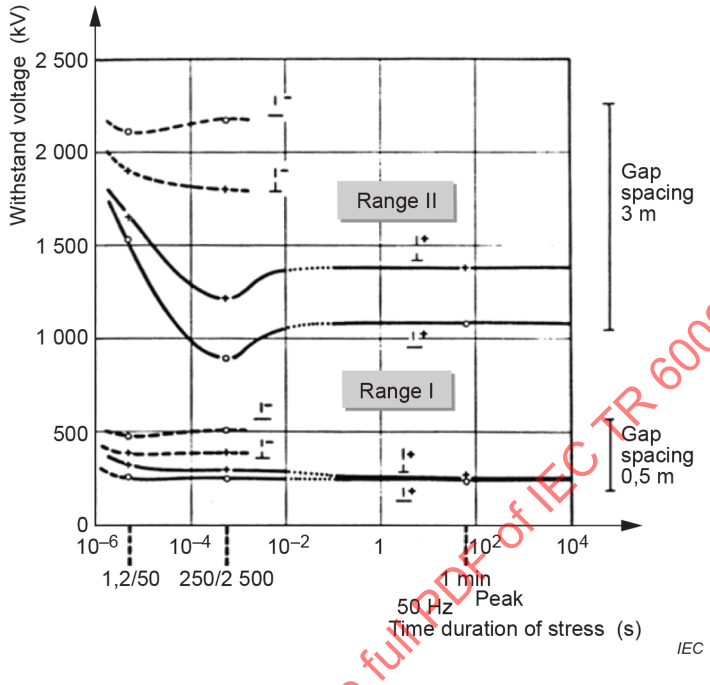



**Figure 2 – Withstand voltage versus duration**

In this test, the minimum switching withstand voltage must be approximately 1,25 times the switching impulse protective level of arresters applied to systems where 245 kV < $U_s$ ≤ 800 kV. In IEC 60099-4 up to edition 2.2, the value of 1,25 was directly required. From edition 3.0, this fixed value has been replaced by the following formula:

$$U = 1{,}1 \times e^{m \times (1000/8150)} \qquad (5)$$

where:

$U$ is the test voltage, in kV;

$m$ is the voltage shape factor.

This formula is based on the barometric pressure formula as a function of altitude and a voltage shape factor $m$, as shown in Figure 2.

Explanation of the formula:

In general, dielectric strength of gases is affected by pressure, temperature and absolute humidity. It increases directly with pressure and absolute humidity, whereas it decreases with increasing temperature. It has been assumed in the standard on insulation coordination (IEC 60071-1) that in most locations worldwide:

- pressure varies only slightly around its mean value.
- temperature and absolute humidity vary largely around their mean values, but their effects on dielectric strength cancel out each other, because the warmer a gas the more humidity it can absorb before going into saturation, which means that the reduction in dielectric strength by increased temperature is compensated by the – in general – automatically higher content of humidity.

Therefore, dielectric strength is only marginally affected by these three environmental parameters. Remaining is the need for compensating the impact of installation altitude, because the absolute pressure (not its variation around the mean value!) has strong dependence on altitude and notable effects on external dielectric strength. This dependence is expressed by the simplified barometric pressure formula (equation 13 of ISO standard 2533):

$$p = p_0 \times e^{-\frac{g_n}{R \times T} \times H} \quad (6)$$

where:

$p_0$ is the normal pressure, expressed in hPa, which is 1 013 hPa.

$g_n$ is the constant of earth acceleration, expressed in m/s$^2$, which is 9,81 m/s$^2$.

$R$ is the specific gas constant of air, expressed in J/(kg·K), which is 287,058 J/(kg·K).

$H$ is the altitude above sea level, expressed in m.

$T$ is the average temperature, expressed in K, which is assumed to be 5 °C (278,15 K), neglecting the gradient of -6,5 K/km.

Then, with altitude $H$ to be inserted, follows:

$$\frac{p}{p_0} = e^{-\frac{H}{8150}} \quad (7)$$

This means that pressure decreases exponentially with altitude, and the same holds true for dielectric strength. As normal service conditions include installation altitudes up to 1 000 m, a minimum installation altitude of $H$ = 1 000 m has to be considered.

Required withstand voltages have thus principally to be corrected (i.e. multiplied) by the inverse function:

$$\frac{p_0}{p} = e^{\frac{H}{8150}} \quad (8)$$

In order to apply this pressure dependence to a voltage correction factor, finally a voltage shape factor $m$ has to be introduced, and the resulting altitude correction factor $K_a$ for required withstand voltages $U_{rw}$, coming from the co-ordination withstand voltage $U_{cw}$ (which in case of arresters is the switching impulse protection level $U_{ps}$), is:

$$\frac{U_{rw}}{U_{cw}} = \frac{U_{rw}}{U_{ps}} = K_a = e^{m \frac{1000}{8150}} \quad (9)$$

where:

$U_{rw}$ is the required withstand voltage, expressed in kV.

$U_{cw}$ is the required coordination withstand voltage, expressed in kV.

$U_{ps}$ is the switching protection level, expressed in kV.

$K_a$ is the altitude correction factor.

$m$ is the voltage shape factor. $m$ = 1 for arresters intended for use in systems of $U_s$ ≤ 800 kV. For arresters intended for use on systems with $U_s$ > 800 kV, $m$ is taken from IEC 60071-2:1996, Figure 9, phase-to-earth insulation, where the value on the abscissa shall be 1,1 times the switching impulse protection level of the arrester.

At this point, all necessary corrections for altitude of installation have been considered. An additional factor of 1,1 finally takes discharge currents possibly higher than the rated switching impulse discharge current into account:

$$\frac{U_{rw}}{U_{ps}} = 1{,}1 \times e^{m\frac{1000}{8150}} \qquad (10)$$



#### 5.4.3.3 Rationale specific to power-frequency voltage test

For arresters applied to systems with $U_s$ ≤ 245 kV, a power frequency test is used instead of a switching impulse test to verify the withstand voltage because such a test results in the lowest withstand voltage of an insulator in Range 1 system voltages (Ranges defined in IEC 60071-1).

In this test, the minimum power-frequency withstand voltage is mandated to be:

- For distribution class arresters: 0,88 × LIPL for 1 min.
- For station class arresters applied to systems with $U_s$ ≤ 245 kV: 1,06 × SIPL for 1 min.

These levels are derived as follows:

- Distribution class arresters: the factor of 0,88 takes into account a safety margin of 1,15 for lightning impulse currents higher than nominal discharge current, an altitude correction factor of 1,13 for 1 000 m installation altitude, a factor 0,8 as a typical ratio between switching and lightning impulse protection level and a test conversion factor of 0,6 × √2 for conversion from switching impulse voltage to peak value of power-frequency voltage according to Table 2 of IEC 60071-2:1996.
- Station class arresters: the factor of 1,06 takes into account a safety margin of 1,1 for higher switching impulse currents, an altitude correction factor of 1,13 for up to 1 000 m installation altitude, and a test conversion factor of 0,6 × √2 according to Table 2 of IEC 60071-2:1996.

### 5.4.4 Evaluation rationale

#### 5.4.4.1 Rationale specific to lightning and switching impulse test

Because arresters are made up of two types of insulation, non-self-restoring insulation on the inside and self-restoring insulation on the outside, the two systems are evaluated differently. Because an internal flashover of an arrester would result in failure of the device, no internal flashovers are allowed in this test up to the claimed withstand limit. Because an external flashover does not automatically cause an arrester failure, two external flashovers are allowed. Two flashovers, out of a total of 15 impulses applied in this test, represents a 10 % flashover probability which is normally accepted in high voltage practice.

#### 5.4.4.2 Rationale specific to power-frequency voltage test

These tests are 1 minute withstand tests without flashover in all cases.

### 5.4.5 Common misunderstandings

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

It should be noted that the impulse withstand levels of arrester housings are not to be compared to basic lightning impulse insulation level (BIL) or critical flashover voltage (CFO) impulse withstand levels of insulators. Due to the arrester's self-protecting nature, the arrester housing can have a lower withstand voltage than the rest of the system without any negative impact on the system withstand level. Also, for this reason and in contrast to other HV apparatus, arresters used in standard applications do not have a standardized insulation withstand rating, as they are specified in IEC 60071-1. The insulation levels for surge arresters are based on the arrester's individual protection levels ($U_{pl}$ and $U_{ps}$, respectively) with a reasonable safety margin added.

# 6 Residual voltage tests rationale

## 6.1 Arrester type for which the tests are applicable

This test applies to all arrester types and voltages.

## 6.2 Purpose of the tests

The purpose of the residual voltage type test is to obtain the data necessary to derive the maximum residual voltage as explained in IEC 60099-4:2014, clause 6.3.

## 6.3 Historical notes

Because surge protection is the most fundamental function of an arrester, testing to characterize the residual voltage of the non-linear resistor elements has always been a part of surge arrester test standards, dating back to the earliest standards for arresters using silicon carbide resistors, and continued into standards for arresters using the current technology of MO resistors.

## 6.4 Tests rationale

### 6.4.1 General

The fundamental purpose of this test is to obtain data pertaining to the residual voltage of MO resistors used in the arresters, to ultimately allow a demonstration that completely assembled production arresters will have residual voltages that do not exceed the manufacturers' published values for specified magnitudes of switching, lightning and steep current impulse.

The primary function of a surge arrester is to limit the voltage appearing across equipment terminals to non-damaging levels when lightning or switching impulses are imposed on an electrical system. Knowledge of the maximum voltage across the arrester under various conditions of surge current magnitude and duration is key to the proper selection of an arrester for a particular application. The maximum arrester voltage for a defined current impulse (arrester protective level) is compared with the dielectric strength of the insulation of the protected equipment to ensure there is adequate protective margin (difference between insulation breakdown strength and arrester protective level). Guidelines for what could be considered adequate protective margin are provided in arrester application guides (for example in IEC 60099-5).

For each arrester within an arrester family, manufacturers typically show in their catalogs the maximum "guaranteed" protective levels for different magnitudes of switching, lightning and steep current impulses. However, in routine testing of arresters, each production arrester is characterized by residual voltage measurement at only one specific magnitude and wave shape of impulse current. In conjunction with the routine test, the residual voltage type test provides a means of verifying that each production arrester does not exceed manufacturers' published protective levels for all specified magnitudes and wave shapes of impulse current.

Since switching surges are not of consequence in medium-voltage distribution systems, no test is required to determine switching impulse residual voltage for distribution class arresters.

It is generally accepted that, on a normalized basis, the impulse V-I characteristics of MO resistors used in a particular arrester family vary very little from resistor to resistor. That is, if the V-I characteristics obtained for all MO resistors were normalized to a particular magnitude and wave shape of current (e.g. 10 kA, 8/20 µs), the characteristics of all the resistors would be coincident to within a very small tolerance. Inherent in this acceptance is that the MO resistors are all of the same diameter and that they have all been processed in a similar manner (e.g. same binder burnout, firing and heat treatment profiles).

It is accepted, and proven by test, that the residual voltage V-I characteristics of a stack of MO resistors can be obtained by a point-by-point summation of the residual voltage characteristics of the individual MO resistors in the stack. Consequently, the residual voltage characteristics of a complete arrester can be determined with good accuracy by testing only a section of a complete arrester. Nevertheless, this is not quite as straightforward for the case of steep current impulses, as is explained in IEC 60099-4:2014, 8.3.2.

### 6.4.2 Sample selection rationale

For the three different residual voltage characteristics to be determined (i.e. switching, lightning and steep current impulse), the test procedure requires that the residual voltage tests be made on the same three samples of complete arresters or arrester sections. By definition, a single MO resistor can be a section of an arrester, and therefore the tests may be (and typically are) performed on three individual MO resistors. While only one section (MO resistor) could be sufficient, three are specified to provide some allowance for minor variations in characteristics within a population of resistors.

It is implied, but not specifically stated, that if an arrester family makes use of more than one diameter of MO resistor, then three samples of each diameter must be tested.

### 6.4.3 Tests procedures rationale

#### 6.4.3.1 Rationale specific to lightning impulse residual voltage test

The lightning impulse residual voltage of an arrester is the voltage across the arrester under "standard" lightning impulses. Each classification of arrester has a specified nominal discharge current at which the arrester voltage must be determined. It is the voltage at this nominal discharge current that is most often used for insulation coordination between the arrester and the protected equipment for lightning surges. However, because lightning impulse currents that an arrester may be called upon to conduct can vary quite widely, users typically desire to know the maximum arrester voltage for a range of lightning impulse current magnitudes. For this reason, the procedure requires measuring the lightning impulse residual voltage at two additional levels, namely at one-half the nominal discharge current and at twice the nominal discharge current (e.g. at 5 kA and 20 kA, in addition to 10 kA, for an arrester with nominal discharge current of 10 kA).

Many manufacturers publish maximum voltages for up to 40 kA, although this is not required by the standard. A user may use the voltage at any current level for insulation coordination purposes, based on knowledge of expected lightning surges and degree of risk willing to be taken.

The current wave shape specified for lightning impulse voltage measurements is designated as 8/20 µs (virtual front time of 8 µs, time to half-crest value of 20 µs). This is a carry-over from the earlier standards for gapped silicon carbide arresters. This wave shape was originally selected because it was approximately the wave shape of the current that would be conducted by a silicon carbide arrester when the arrester was subjected to a 1,2/50 µs lightning impulse voltage sufficient to cause the arrester gaps to spark over. The 1,2/50 µs wave shape is considered a more-or-less standard lightning surge voltage wave shape and is used routinely for testing of lightning insulation withstand capability of equipment (e.g. transformers, circuit breakers, insulators).

For each of the three current levels, the highest voltage measured among the three samples is taken to determine the lightning impulse residual voltage of complete arresters.

#### 6.4.3.2 Rationale specific to switching impulse residual voltage test

The switching impulse residual voltage is the voltage across the arrester for "standard" switching impulse currents. The impulse current wave shape to be used is not precisely defined, the requirement being only that the virtual front time is in the range 30 to 100 µs and time to half crest value of approximately twice the virtual front time. In earlier standards for testing of silicon carbide arresters, the impulse current was required to be a more-or-less square wave of at least 2 000 µs duration, generated by a distributed constant generator, this being considered as being fairly representative of switching impulse currents in practical transmission systems. The impulse current wave shape now specified for metal-oxide arresters is more conveniently produced in the laboratory with a lumped L-C circuit, and results in virtually the same residual voltage as for the longer duration current previously specified for silicon carbide arresters.

For typical switching impulse current magnitudes, a station class arrester will be operating in a very highly non-linear portion of its U-I characteristic, and voltages do not vary a great deal over a fairly wide range of current magnitudes in this region. For this reason, the procedure requires that switching impulse residual voltage be measured for only one current magnitude, the specific level being dependent on the class of the arrester (SL, SM or SH).

The highest voltage measured among the three samples is taken to determine the switching impulse residual voltage of complete arresters.

#### 6.4.3.3 Rationale specific to steep current impulse residual voltage test

##### 6.4.3.3.1 General

The steep current impulse residual voltage is the voltage across the arrester for impulse current with faster rise time than that associated with standard lightning impulses. Such steep current impulses can result from external flashover of transmission line or substation equipment.

For arrester characterization purposes, the impulse wave shape is specified as one having a virtual front time of 1 µs and time to half crest value of not more than 20 µs. MO resistor residual voltages for such impulse currents are higher than for the same magnitude lightning impulses (specified as having an 8/20 µs wave shape).

The ratio between the steep current impulse residual voltage and the lightning impulse residual voltage for a given current magnitude is essentially independent of the actual magnitude (dependent only on wave shape), and therefore it is necessary only to obtain the steep current impulse residual voltage at one current magnitude (specified to be the magnitude of the nominal discharge current for the arrester) rather than for the three magnitudes used for the lightning impulse residual voltage test.

##### 6.4.3.3.2 Special considerations

For steep current impulses, because of the high rate of rise of current on the wave front in comparison to the lightning and switching current impulse waveshapes, the inductance of any metallic spacers interspersed in the MO resistor stack and the inductance of the MO resistors themselves have an influence on the total voltage that appears across the terminals of the arrester. The terminal voltage is the sum of the residual voltage, $U_{res}$, of the MO resistors excluding any inductive effect and the voltage drop across the series inductance, $L$:

$$U_{arr} = U_{res} + L\frac{di}{dt} \quad (11)$$

where:

$U_{arr}$ is the terminal voltage of the arrester, expressed in kV.

$U_{res}$ is the sum of the residual voltage of the MO resistors excluding any inductive effect, expressed in kV.

$Ldi/dt$ is the voltage drop across the series inductance, expressed in kV (where di/dt is the rate of change of current).

The $U_{res}$ portion of this total voltage can be obtained from residual voltage measurements on individual MO resistors if steps have been taken to extract the inductive voltage component from the measurements. The means for accomplishing this are specified in the test procedure and consists of three steps:

- Step 1: measure the residual voltage of the MO resistor using the specified 1 µs virtual front time impulse current.
- Step 2: measure the impulse voltage across a metallic non-ferrous disk of the exact same dimensions as the MO resistor, using the same impulse current amplitude and wave shape of step 1.
- Step 3: subtract the peak voltage measured in step 2 from the peak voltage measured in step 1.

The highest value obtained from step 3 among the three samples is taken to determine the non-inductive portion ($U_{res}$) of the steep current impulse residual voltage of complete arresters.

To obtain the arrester voltage including inductive voltage impact, the effect of the self-inductance voltage has to be re-introduced by calculating the inductive voltage drop of the arrester (including the MO resistor inductance and the inductance of all series-connected metal components) and adding it to the non-inductive portion voltage from above.

This inductive voltage is given by:

$$L\frac{di}{dt} = L' \times h\frac{di}{dt} \quad (12)$$

where:

$L$ is the inductance of the arrester unit, expressed in µH.

$L'$ is the inductance per meter of the arrester, expressed in µH/m, with 1 µH/m for air insulated arresters, 0,3 µH/m for GIS and separable and dead-front arresters.

$h$ is the length of the arrester, expressed in m.

$di/dt$ is the rate of change of current through the arrester with respect to time, expressed in A/µs.

The values of the inductance layers (1 µH/m for AIS arresters, 0,3 µH/m for GIS arresters) were introduced to IEC 60099-4:2001. This refers to the work performed in CIGRÉ WG 06 of Study Committee 33 (published e.g. in ELECTRA Dec. 1990, pp. 133 – 146). Under reasonable assumptions concerning the distance of the return path, the value of 1 µH/m can be calculated for a linear, stretched arrester design as typically applied for AIS arresters. As well, for a simple linear coaxial cylinder configuration a value of 0,3 µH/m can be theoretically achieved by appropriate choice of the boundary conditions. This value of 0,3 µH/m is doubtful, however, for a GIS arrester of internal "folded" arrangement of the MO resistor columns (i.e. one electrical, three mechanical columns). Here a value of 1 µH per meter of arrester length seems more realistic. But this has not been considered in IEC 60099-4 so far and may become subject to future discussion in the arrester working groups.

Strictly, the inductive voltage should be added to the non-inductive voltage on a point-by-point basis over the entire duration of the impulse, and the resulting peak value be taken as the steep current impulse residual voltage of the arrester. However, it has been demonstrated that very little error is introduced if the rate of change of current is simply stated to be the impulse current magnitude divided by 1 µs and this value is simply added to the peak value of non-inductive portion of the voltage. The rate of change of current is then simply 2,5, 5, 10 or 20 kA/µs for arresters with nominal discharge currents of 2,5, 5, 10 or 20 kA, respectively.

Then the $L\frac{di}{dt}$ inductive voltage adders simply become:

- for air insulated arresters (inductance taken as 1 µH/m): 2,5, 5, 10 or 20 kV/m of arrester length, respectively.
- for GIS and separable and dead-front arresters (inductance taken as 0,3 µH/m): 0,75, 1,5, 3 or 6 kV/m of arrester length, respectively.

NOTE The inductive voltage "correction" is specified only for determination of steep current impulse residual voltage. For lightning impulses (8/20 µs wave shape), the rate of change of current and therefore the inductive voltage contribution, is an order of magnitude less than for steep current and can be ignored.

### 6.4.4 Evaluation rationale

No evaluation criterion is included in this test. The measured residual voltages are published by manufacturers and used for insulation coordination purposes.

## 7 Test to verify long term stability under continuous operating voltage rationale

### 7.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages.

### 7.2 Purpose of the test

The test is an accelerated ageing test, performed on individual MO resistors, to provide assurance that they will exhibit stable operating conditions in terms of power loss over the anticipated lifetime of the arrester.

### 7.3 Historical notes

This test was first introduced into the standards when the MO arrester era began. It was then a "procedure" within the operating duty test. With very little historical experience with this type of material, this procedure was used because it was considered the best available method of predicting material ageing at the time. It was assumed that electrical ageing follows the Arrhenius Law. There is no scientific evidence that MO resistors would age according to this model, and quite obviously, it is definitely not the case if power losses continuously decrease during the test, but the specified test procedure is still considered the best available method.

In IEC 60099-4:2006, a "*test procedure for resistor elements stressed at or above the reference voltage*" was added in order to also cover arrester designs with extremely uneven axial voltage distribution. Under applied test voltages of reference voltage level or higher, the standard test procedure cannot be performed anymore, because individual MO resistors would experience thermal runaway under these conditions.

Up to IEC 60099-4:2009, power losses were allowed to increase. If they doubled, as a maximum, suited correction factors of the test voltages in the operating duty tests had to be used. If they increased by more than two times the aged resistors had to be directly used in the operating duty tests.

In IEC 60099-4:2014, "procedure" was changed to a "test" with individual pass criteria. The reason for the change was that at this time, the ageing behavior of an arrester was considered important enough that its verification by an individual type test was justified, thus giving this aspect more importance. It was also considered state of the art, more than 35 years after introduction of this technology, to manufacture MO resistors that do not exhibit increase of power loss during the test period (and over the anticipated lifetime of an arrester). There was no reason any more to allow for MO resistors that exhibit power losses, which increase after having gone through a minimum, or which are higher at the end of the test than at the beginning. This was an important change in test philosophy.

## 7.4 Test rationale

### 7.4.1 General

Besides seal leakage of the housing, electrical ageing of the metal oxide resistors is considered one of the potential limiting factors of the lifetime of an arrester. Electrical ageing (or degradation) would affect the voltage current characteristics in the leakage current range rather than in the high current range, which means that an arrester's protection level is not expected to change during its lifetime, but the leakage current might do so. Normally, once an arrester is energized at power frequency voltage, power losses would decrease to some stable final level. On the contrary, electrical ageing would mean that power losses increase from the beginning or after a certain time of operation. While this would not be critical in normal operating conditions, thermal stability after energy injection may be impaired by the increased power losses, when the arrester is close to its specified thermal stability limit. It is thus important to demonstrate by this test that the MO resistors do not suffer any electrical degradation. An elevated test temperature has been introduced as an acceleration factor. Even though it might not be the case when power losses decrease with time, the historical assumption has been that electrical aging follows the Arrhenius Law. With the maximum ambient temperature of 40 °C (normal service conditions in open air substations) and the specified test temperature of 115 °C, the test duration of 1 000 h theoretically represent an operating time of 110 years (with an assumed acceleration factor AF = $2,5^{(115-40)/10}$).

For dead-front arresters and liquid immersed arresters only, as stated in IEC 60099-4:2014, 12.8.4 and 13.8.4, the upper limit of the ambient temperature of the medium in which the arrester operates is higher, respectively 65 °C and 95 °C. With such upper limits of the ambient temperature, instead of 110 years, a test duration of 1 000 h would theoretically represent an operating time of 11 years and 0,7 year, respectively, which is not sufficient. To improve the situation, increasing the test temperature, test voltage or test duration could be considered. In general, it is not acceptable to increase the test temperature above 115 °C as it may change the physics of ageing, rendering the Arrhenius law non-applicable. Increasing the test voltage is not acceptable either, as this factor is not established as an acceleration factor. The only remaining possibility is to increase the test duration and steps to obtain theorical equivalent operating time resulting from tests in IEC 60099-4:2014, 12.8.4 and 13.8.4, are presented below.

The test to verify long term stability under continuous operating voltage is not a full long term stability aging test but is rather considered as a screening test intended to reject materials and production quality which are inadequate. This test is not intended to predict long term performance for arresters designs under cumulative service stresses and it should be understood that life expectancies in Table 2 are given for information only and should not be mixed up with a guaranteed lifetime. They are rather just the mathematical results of life expectancy, assuming MO resistors would perfectly follow the Arrhenius law.

$$AF_{T_{\text{test}}} = 2{,}5^{\left[ \left( T_{\text{test}} - T_{\text{a,max}} \right) / 10 \right]} \tag{13}$$

where:

$AF_{\mathrm{Ttest}}$ is the acceleration factor at the test temperature.

$T_{\mathrm{test}}$ is the test temperature, expressed in °C (set to 115 °C).

$T_{\mathrm{a,max}}$ is the maximum ambient temperature of the medium in which the arrester operates, expressed in °C.

And with $T_{\mathrm{a,max}}$:

$$t_{\mathrm{Ta,max}} = \frac{t_{\mathrm{test}} \times AF_{\mathrm{Ttest}}}{24 \times 365} \tag{14}$$

where:

$t_{\mathrm{Ta,max}}$ is the equivalent operating time at $T_{\mathrm{a,max}}$ , expressed in h.

$t_{\mathrm{test}}$ is the time duration of the test, expressed in h.

**Table 2 – Calculated minimum life expectancy if MO resistors would perfectly follow the Arrhenius law**

| Arrester type | $T_{\mathrm{a,max}}$ °C | $AF_{115}$ - | $t_{\mathrm{test}}$ h | $t_{\mathrm{Ta,max}}$ Years |
|---|---|---|---|---|
| General case | 40 | 965 | 1 000 | 110 |
| Dead-front | 65 | 97,7 | 2 000 | 22 |
| Liquid-immersed | 95 | 6,25 | 7 000 | 5 |

For liquid immersed arresters only and after agreement between the user and the manufacturer, the standard allows to use a shorter test time (2 000 h) followed by an extrapolation to obtain $P_{\mathrm{end}}$ (the power losses at the end of the test, e.g. at 7 000 h instead of 2 000 h in such case).

For more information on this topic, see CIGRE TB696, chapter 3.

### 7.4.2 Sample selection rationale

The test is performed on three MO resistors though a notable statistical spread is not expected for this aspect of MO resistor performance. This is to compensate for small variations (e.g. slightly different temperatures within the allowed tolerances) of the test conditions, which might have effect on the test result, as MO resistors have distinctly non-linear properties. To provide some assurance that a test does not result in an overly optimistic or pessimistic measure of performance it is typical to test more than one sample to demonstrate repeatability.

All material (solid or liquid) in direct contact with the MO resistors in the arrester shall be present during the ageing test with the same design as used in the complete arrester. Especially for arrester designs with an enclosed gas volume, in case of moisture ingress or excessive internal radial field stress, the medium surrounding the MO resistor within the arrester may be subject to a modification during the normal life of the arrester due to internal partial discharges. Internal partial discharges may change the gas composition surrounding the MO resistors to become of reducing (i.e. oxygen consuming) nature and can trigger degradation and increase power losses. The intrinsic ageing behavior of the MO bulk material is known to be a grain boundary phenomenon. An excess of oxygen has been shown to be essential for the electrical characteristics of an MO resistor. Migration of charged defects within the space charge regions and the reduction of the excess oxygen at the grain boundaries are expected to take place or have been observed during accelerated ageing tests. As a general finding, oxygen in the surrounding atmosphere helps for the long-term stability, whereas a reducing atmosphere may have negative effects on the stability of the rim area of an MO resistor.

Because a suitable test procedure taking into account such modifications is not yet known, an alternative procedure consists in performing the test in $N_2$ or $SF_6$ to represent a low oxygen concentration (less than 0,1 % in volume). This would ensure that even in the total absence of oxygen the arrester will not age. However, this is stated in a note only and is thus not mandatory.

#### 7.4.3 Test procedure rationale

Because electrical ageing will result in increased power losses at a given temperature, power losses are to be measured in fixed time intervals during the test. The test voltage is the continuous operating voltage corrected for effects by uneven axial voltage distribution of the related arrester design. It has to be determined by appropriate means (calculation, simulation, measurement) of evaluating the arrester's axial voltage unbalance. If the resulting test voltage equals reference voltage or is even higher, the test cannot be performed any more under constant voltage conditions, because the resistors will suffer thermal runaway. In this case, the test shall be performed at constant power losses rather than at a constant test voltage, and the power losses at continuous operating voltage are measured during short interruptions of the test at given time intervals.

#### 7.4.4 Evaluation rationale

If the MO resistors exhibit power losses at the end of the test greater than 1,1 (this factor to cover typical measuring uncertainties in power loss measurement) times the start value, or if after passing a minimum power loss increase again by a factor of more than 1,3 referred to this minimum, then this type of MO resistor is not suitable for use in arresters that are continuously energized.

## 8 Test to verify the repetitive charge transfer rating ($Q_{rs}$) rationale

### 8.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages.

### 8.2 Purpose of the test

The fundamental purpose of this test is to verify the maximum impulse charge transfer that may be handled by an arrester. Charge has been chosen as a test basis for the purpose of better comparison between different makes of metal oxide resistors and arresters.

### 8.3 Historical notes

Since long ago the current withstand capability for a 2 ms rectangular current impulse has been used by the manufacturers to rate their arresters and given in manufacturers' catalogues. They usually named this value the "long duration withstand current capability". However, the test to verify the rating has in general been unspecified, i.e. in number of applications, grouping of impulses and time between impulses and groups.

The long-duration or line discharge test (LDT) has been used in the IEC 60099 standard series to verify energy capability. However, since the severity of this test is dependent on the protection level of the arrester, it is possible to claim a higher class by using a higher residual voltage. The actual energy or charge capability of the MO resistors may also not have been shown in the test. When the work to make a revision of the standard started, therefore, a discussion how to replace the LDT with a more suitable test started.

In addition, the previous tests do not give any information of the statistical failure risk of the MO resistors and complete arresters for the claimed rating. A more statistical approach for a revision was therefore agreed upon in IEC Technical Committee 37. The work started prior to 2010.

### 8.4 Test rationale

#### 8.4.1 General

Surge arresters are subjected to current impulses from lightning or switching events. Therefore, it is necessary to know the capability of the arresters in measure of the charge transferred by the arrester during such events. In addition, the withstand capability of MO resistors is a statistical parameter and a high-voltage arrester can contain a significant number of MO resistors. If a single MO resistor fails, the probability is high that the complete arrester would fail. Distribution arresters contain only one or a few MO resistors. On the other hand, the applied number of distribution arresters is very high, and many arresters may be stressed at the same event. A type test, therefore, which quantifies the failure risk for a certain charge, is very rational.

#### 8.4.2 Sample selection rationale

The selection takes into account that normally it is considered more difficult to manufacture a taller than a shorter MO resistor from homogeneity point of view. Thus, a taller block shall be tested if blocks with the same diameter but with different lengths are manufactured. However, to avoid that a shorter block with much higher relative voltage stress is qualified by the test of a taller block with the same rated charge but with lower relative voltage stress, the test charge shall be increased as specified. This is because for the same charge, the energy absorbed by the MO resistor will be higher for higher residual voltage.

For one type of MO resistors, the diameter shall be the same. This is because it could not be assumed that the homogeneity of a smaller diameter block is the same as that for a bigger diameter block and that the withstand charge density is independent of diameter for the same relative voltage stress of the MO resistors.

Ten samples shall be tested (or 20, if 2 samples fail in the first test sequence) in order to statistically verify a reasonable failure risk. With only three test samples, as earlier specified, the statistical information will not be sufficient.

#### 8.4.3 Test procedure rationale

The number of test samples and applied impulses are selected to verify that the rated charge transfer given by the manufacturer is verified with a certain statistical risk of failure. The test values are also specified 10 % above rated values in order to be able to apply the same charge rating to a complete arrester, containing many MO resistors, as to single MO resistors. See Figure 3.



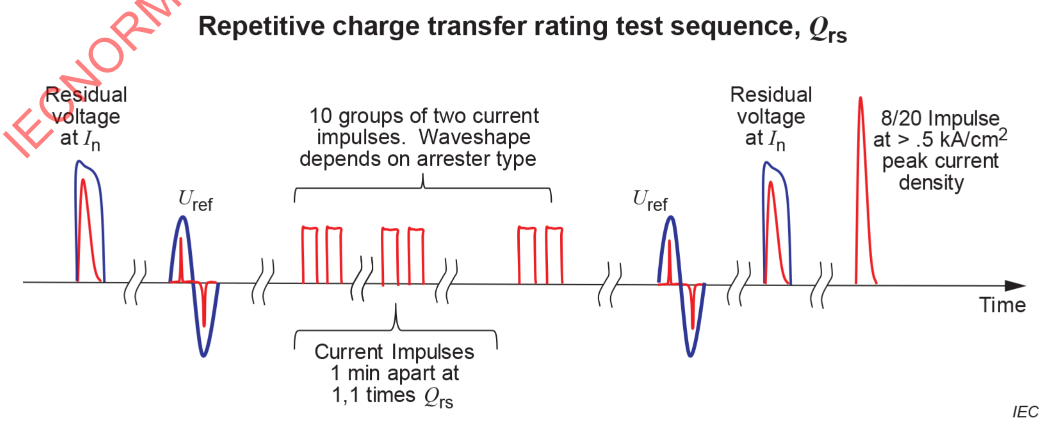



**Figure 3 – Sequence of the test to verify the repetitive charge transfer rating**

Test event relevance:

- Measure Residual Voltage at $I_n$: This is to check for change of residual voltage to verify if the impulse sequence affects the protective characteristic.
- Measure $U_{ref}$: Looking for electrical degradation that could affect stable operation during the life of the arrester
- 1,1 × $Q_{rs}$ Impulses: This impulse sequence is intended to stress the MO to represent a life time of duty. Groups of 2 are used for time expediency. The applied factor of 1,1 accounts for the fact that only individual MO resistors are tested, but in the arrester standards information shall be achieved upon full arresters. It is, therefore, requested that the individual MO resistors shall have a 10 % higher $Q_{rs}$ capability than specified for a complete arrester made from these resistors.
- Last impulse for pre-damage: a test current that reveals mechanical damage.

Only single polarity is allowed for the unipolar waves (same time duration and polarity). Using single polarity may polarize the material, which makes the test harder to pass.

#### 8.4.4 Evaluation rationale

If only one failure occurs during the first sequence and this happens, in the worst case, at the very first impulse application, 180 impulses without failure will have been applied at the end, giving a failure probability of maximum 1/181 = 0,005 5 or 0,55 % for the complete test. If two failures occur during the first sequence and this happens, again as a worst case, at the very first applications on two of the samples, 360 impulses without failure will have been applied at the end of both sequences, giving again a failure probability of maximum 2/362 = 0,005 5 or 0,55 % for the complete test. This still does not give total confidence in the required low failure rates (below 1 %), especially of complete high voltage arresters, where several hundreds of MO resistors may be stressed at the same time. But it is better than the former LDT where three samples had to be tested by 18 impulses each and no failure was allowed to occur. That procedure could just indicate that the failure rate might be better than 1/54 = 1,85 %. The test procedure in IEC 60099-4:2014 is thus considered a reasonable compromise between acceptable test effort and information about failure probabilities.

In the former LDT, only a visual inspection of the test samples was required for evaluation, thus looking only for mechanical damage of the samples. In the $Q_{rs}$ test, additional criteria have been introduced, because failures are not just of mechanical nature, but also changes of the electrical characteristics indicate fatigue of the material. Any change of the reference voltage and of the residual voltage at nominal discharge current shall be within ± 5 %. Thus, two important regions of the U-I characteristic are checked: the leakage current region, which is relevant for thermal stability under TOV and normal operating voltage conditions, and the protective characteristic. Allowed changes within ± 5 % are reasonable limits, which have always been used in the arrester standards whenever changes are to be evaluated. It is also in line with the energy handling test procedures developed and applied by CIGRE (see CIGRE TB 544), which gave major input to IEC 60099-4:2014 when this test was added.

#### 8.4.5 Common misunderstandings

The repetitive charge transfer rating $Q_{rs}$ and the rated thermal energy $W_{th}$ (or $Q_{th}$ for distribution class arresters) shall not be compared to one another because, among others, they differ with regards to: purpose of the test, test specimen (MO resistor versus thermally prorated section), test procedure (e.g. thermal stability with voltage application after the $W_{th}$ test), waveshape used in the test, etc.

# 9 Heat dissipation behavior of test sample rationale

## 9.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages.

## 9.2 Purpose of the test

The purpose of this test is to verify that a pro-rated section of an arrester has the same or more conservative cooling behavior compared with the arrester that is represented by the pro-rated section. This is needed for all tests where thermal stability is required.

## 9.3 Historical notes

In IEC 60099-1:1999 (now withdrawn), 8.6, it is stated that *"The test sample including grading components is either assembled in a housing of the same design as that to be used in service or mounted in a sealed enclosure. The enclosure shall be designed to reproduce the same heat capacity and thermal losses, with special reference to the axial heat transference, as would occur if the actual arrester were tested. Details of the design of the test enclosure, mounting and connection arrangements, together with the results of any tests carried out to demonstrate the thermal equivalence of the tests and service arrangement, shall be given."* No guidance was given on how a test procedure should be to prove the thermal equivalency.

In IEC 60099-4:1991, for the first time a subclause (7.5.3) was introduced with the title "Heat dissipation behavior of test sample". In this subclause, a thermal model was described in detail that represents an electrically and thermally sliced portion of the arrester being modeled. Due to the relatively simple design, a "slice" could be cut out of a complete arrester, or a "slice" of the arrester housing, which was at that time a porcelain housing. The pro-rated active part was then arranged in the porcelain section in the same way as it was in the complete arrester. Further, reference was given to an Annex B, where a test was described to verify thermal equivalency between complete arrester and arrester section.

In all editions of IEC 60099-4 prior to edition 3 (2014), the pro-rated section of an arrester was an appropriate electrical, dielectric and thermal model of the arrester. But the requirements for each of these models are partly contradicting with each other. For example, in a very short prorated section that has the same cross section as the real arrester ("a slice of an arrester"), more heat will be axially dissipated and more influence of the terminals (thermal conductivity, heat capacitance) will be present than in the real arrester, which can be considered an infinitely long structure without any heat flow in axial direction. In IEC 60099-4:2014, the test to prove the dielectric performance was separated from the thermal electrical tests. However, in case the pro-rated section represents both features, it can be used for both tests.

In IEC 60099-4:2014, the test to verify thermal equivalency between complete arrester and arrester section remained in principle the same but was rewritten to give more precise guidance based on the experience with the test procedure. The temperature to be reached for the start of the cooling down period was increased from approximately 120 °C to at least 140 °C. The reason for this increase was because it was closer to the temperatures typically reached during an operating duty test.

## 9.4 Test rationale

### 9.4.1 General

A thermal equivalency test has been developed to permit the use of thermally prorated section of an arrester (with lower rated voltages) in many tests of IEC 60099-4:2014, as full scale arresters may be challenging to test for practical reasons in laboratories.

### 9.4.2 Sample selection rationale

For this test, the thermal characteristic of the arrester and prorated section, which has minimal statistical scatter, is more important than the electrical characteristics.

The test sample shall be a thermally pro-rated section of the arrester, which means that the pro-rated section has the same or a conservative cooling behavior as compared to the represented arrester. It is not necessary that the pro-rated section be a slice out of the actual arrester. It is allowed to use a different design or housing, as long as the cooling behavior of the prorated section represents the actual arrester.

### 9.4.3 Test procedure rationale

The intended purpose of the test is to have a pro-rated section of the modeled arrester with the same or more conservative cooling performance. In the described test procedure, a mean value of the temperature of the active part is evaluated by measuring the temperature at different points along the column of the MO resistors. The mean value is used because of thermal self-grading effects in the MO column. Guidance is given in the IEC 60099-4 so that the most conservative temperature is found.

It is important to note that the time to heat the actual arrester and the prorated section should be approximately the same and that the duration of the heating shall not exceed one hour. Under real service conditions, an arrester's active part is heated adiabatically within a time of microseconds or milliseconds. Therefore, the active part will experience a temperature "jump", while all other components (internal supporting structure, housing) will remain at the steady state temperature. Then, heat exchange will start to take place, and in the very beginning the active parts will cool down, whereas the surrounding elements will heat up. Finally, after a certain time, all components will cool down. This is a rather complex heat exchange process, which would best be represented in the laboratory by impulse energy injection to the complete arrester. This is not possible, though, and as a compromise, heating by power-frequency current is allowed. This ought to be done in a time as short as possible, and some laboratories have powerful test transformers that allow heating to the required temperature in five to ten minutes. But other laboratories might need much longer time due to weaker test transformers. But if the heating time exceeds an hour or so, the heat exchange process is no longer realistic and potentially too conservative. It was decided, therefore, that a maximum time of one hour can reasonably be required and accepted as a compromise, which should allow most of the high-voltage laboratories worldwide to run this test.

### 9.4.4 Evaluation rationale

The derived cooling curve of the pro-rated section should lie at all measured times on or above the cooling curve of the MO arrester. See Figure 4.

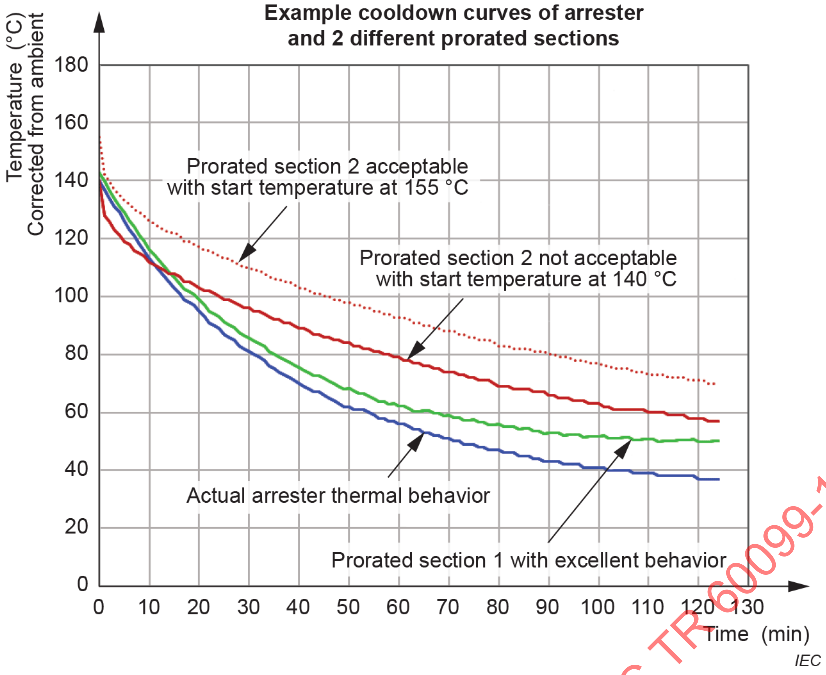



**Figure 4 – Example of cooldown curves of test samples**

## 10 Operating duty test rationale

### 10.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages.

### 10.2 Purpose of the test

The purpose of this test is to verify that the arrester will always remain thermally stable after duty while in service over its expected life including possible electrical ageing. It is also the purpose of this test to ensure that the protective characteristic is not significantly changed by such duty.

### 10.3 Historical notes

This test has origins in the IEC 60099-1 test standard and was further modified with the introduction of IEC 60099-4:1991, which had been studied for over 10 years since 1980. Then, in IEC 60099-4:2014, 6 points were mainly changed:

- The accelerated ageing test, which had been a procedure within the operating duty test, became an independent test that does not permit the increase of power loss due to the ageing by the system voltage.
- The pre-conditioning test of 20 impulses of nominal discharge current $I_n$ preceding the two high current impulses or one high current impulse was deleted. This pre-conditioning had been a part of the operating duty test for silicon carbide gapped arresters, in which a large follow current flowed after the operation of the gaps thereby aging them. In metal-oxide surge arresters without gaps, however, this is no longer necessary.
- The arrester classification with nominal discharge current of 1,5 kA was removed because it was not used in practice.

- For the station class arrester, the rated thermal energy $W_{th}$ was introduced instead of two long duration current impulses (that represented a single field service condition), because it was clarified in the activity of CIGRE WG A3.17 that the important condition for the verification of thermal stability was the temperature increase from the dissipated energy rather than the number of impulses. In addition, the necessary energy was difficult to achieve in UHV arresters due to the limitation of the test facilities.
- For the distribution class arrester, the rated thermal charge $Q_{th}$ was introduced instead of two impulses of high current because it was clarified in the activity of CIGRE WG A3.17 that the important condition for the verification of thermal stability was the total charge of the impulses rather than the number of impulses.
- The thermal section construction requirements were changed because the test sample did not have to just represent a sliced portion of the active part of the arrester but more importantly needed to be a thermal equivalent of the complete arrester as demonstrated in the ""Heat dissipation behavior of test sample"" section of IEC 60099-4.

## 10.4 Test rationale

### 10.4.1 General

If an arrester absorbs energy from a system event (e.g. lightning impulse, switching surge, temporary overvoltage), the temperature of the MO resistors may rise to a point that is beyond the arrester's ability to thermally recover to its previous steady state condition. Arrester manufacturers are required to specify values for energy ($W_{th}$ for station class arresters) or charge ($Q_{th}$ for distribution class arresters) that represent the thermal limit for each arrester type. The operating duty test verifies that the arrester will thermally recover after absorbing energy (or transferring charge) up to the specified rating.

### 10.4.2 Sample selection rationale

There are two parts of the operating duty test: a MO resistor conditioning part and an energy injection and thermal recovery part. The purpose of the conditioning part is to apply electrical aging to the MO resistors, and may be performed with MO resistors alone, although it is also acceptable to perform the aging with MO resistors assembled in a dielectrically prorated section.

The energy and thermal recovery part of this test is carried out with thermally prorated sections, because the purpose of this part is to demonstrate the thermal stability of the arrester design.

The samples are selected in order to represent the most onerous conditions and the samples must result in the maximum heating per unit of MO resistor volume. This is accomplished by using MO resistors with the highest residual voltage per unit length of the design, and minimum $U_{ref}/U_r$ ratio.

See IEC 60099-4:2014, Annex K for example of calculating the test voltages.

Though thermal stability has basically no statistical character, the test is performed on three samples to compensate for statistical factors such as incorrect voltage adjustment, variability in the power loss characteristic, tolerance during energy injection etc.

### 10.4.3 Test procedure rationale

Prior to IEC 60099-4:2014, 20 lightning impulses were used to age the samples but as an outcome of recent research, lightning impulses do not significantly affect aging in MO resistors. The conditioning part is therefore carried out by applying only one or two high current impulses for ageing. It is understood that the high current impulses have the highest impact on ageing, where the first impulse has a more dramatic effect on ageing than the second. See Figure 5.

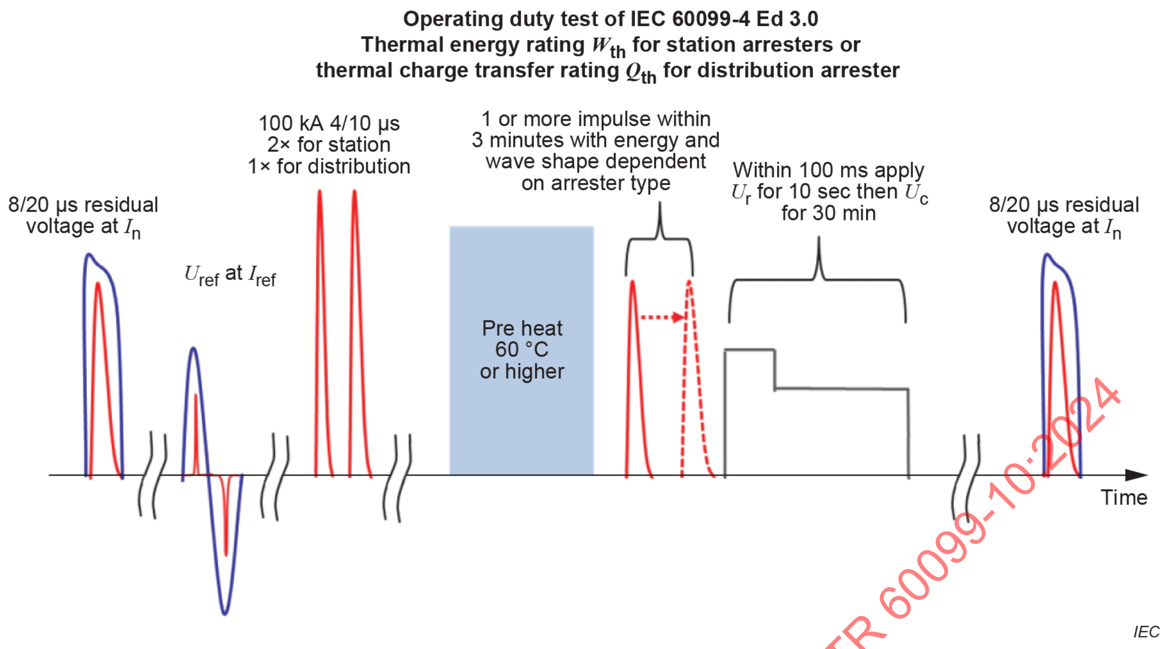



**Figure 5 – Operating duty test sequence**



Station class arresters of 10 kA and 20 kA are aged by two 100 kA impulses, which current value came from the standard IEC 60099-1 for the gapped surge arresters.

For distribution class arresters, historically also two high current impulses were used, the first one for ageing, and the second one for energy injection in the thermal recovery part of the test. This approach was considered a too severe and at the same time unrealistic stress for distribution arresters and was therefore changed in IEC 60099-4:2014. To date, only one high-current impulse is applied for ageing, whereas the energy is injected by two lightning current impulses.

For station class arresters, the application of two high-current impulses was kept, as this is not a too severe stress to the MO resistors typically used. The current density at 100 kA amplitude is much lower in a station class arrester than in a distribution arrester, which justifies the different approaches.

It should finally be mentioned that the high-current impulse has mainly two purposes in arrester testing: It causes ageing due to its high front steepness and amplitude, and it is the only way to produce high dielectric stress to the arrester, which could not be achieved by impulse voltage testing due to the voltage limiting characteristic of the MO resistors. It requires a very high current amplitude to increase the residual voltage to values considerably higher than the lightning impulse protection level.

The sample is preheated to the temperature of T-start, normally 60 °C, to represent the effect of the temperature rise from the ambient temperature of 40 °C due to continuous operating voltage, power loss vs. temperature characteristics, heat dissipation performance of the arrester, voltage distribution along the MO-resistors in the arrester, $U_c/U_{ref}$ ratio (continuous operating voltage/reference voltage), pollution of arrester housings, solar radiation, etc. For the arresters used in the systems of $U_s$ up to 800 kV, the long-term experience of over 30 years in the actual field has shown that the present T-start of 60 °C covers all these effects sufficiently.

But in the emerging technologies of the arresters for the systems above 800 kV, lower protection levels and more compact designs are desired. Therefore, IEC 60099-4:2014 requires carrying out the temperature rise measurement for the arresters used in the systems of $U_s$ > 800 kV and to use the obtained temperature (weighted mean temperature) as T-start.

It is assumed that when the "complete test samples" have reached the start temperature, as stated in IEC 60099-4:2014, the MO resistors themselves also have.

For dead-front arresters and liquid-immersed arresters, T-start is 85 °C and 120 °C respectively because the operating or ambient temperature at normal condition is higher than that of the other arresters.

For station class arresters, rated thermal energy $W_{th}$ is applied within maximum 3 minutes by one or more 2 to 4 ms long duration current impulses or by a 2 to 4 ms unipolar sine half wave current impulses, which wave is adapted to give more flexibility in testing and the effect is the same.

The purpose is just to inject energy and heat the sample to the temperature that is corresponding to $W_{th}$, while the actual way of energy injection is of less importance. Particularly, it has been found that the waveshape of the impulses (rectangular, sinusoidal) is not as important in the few ms time frame. Ideally the energy would be injected in one impulse, but this is not practical due to laboratory limitations, so three minutes are allowed for the injection. Experience has found this to be a reasonable compromise during which time the sample does not significantly cool.

The energy $W_{th}$ corresponds to the switching surge duties on the systems. Many classes of thermal energy rating are prepared to cover various kinds of arresters currently used in the world.

For distribution class arresters, rated thermal charge transfer $Q_{th}$, rather than rated thermal energy $W_{th}$, is injected within one minute by two lightning current impulses 8/20 µs, because lightning is the main duty and it is a current source. This takes into account that, though only charge is transferred and specified, the arrester of course dissipates energy. Therefore, charge transfer may cause thermal stability problems and must be tested for this aspect. There are three classes of distribution arresters, 2,5 kA, 5 kA and 10 kA, and each class has only one thermal charge transfer $Q_{th}$.

The last part of the test sequence demonstrates the thermal stability after application of rated voltage $U_r$ for 10 s and then continuous operating voltage $U_c$ for 30 minutes. The application of $U_r$ at the start of thermal recovery is to simulate worst case scenarios on systems after experiencing duty.

This application of $U_r$ reflects TOV system conditions during which the arrester must be able to handle specified energy. Since energy injection can occur any time during a TOV event, injecting at the beginning of the time period is the worst case.

The rated voltage is applied within 100 ms after the last impulse. This time interval may be zero in the actual system phenomena, but the interval of 100 ms is allowed for practical laboratory limitations.

This test scenario results in excess power losses in the MO resistors due to the extremely temperature dependent voltage-current characteristic, which may cause notable extra stress with regard to thermal stability. This is considered in the thermal recovery phase of the test.

#### 10.4.4 Evaluation rationale

The three evaluation criteria, thermal recovery, no physical damage and change of residual voltage within the limits, verify that the arrester design meets the fundamental purpose of this test.

The residual voltage assessment is to ensure that the protective level has not changed and ± 5 % is the accepted criterion for all tests in this series.

### 10.4.5 Common misunderstandings

The repetitive charge transfer rating $Q_{rs}$ and the rated thermal energy $W_{th}$ (or $Q_{th}$ for distribution arresters) shall not be compared one to another because, among others, they differ with regards to: purpose of the test, test specimen (MO resistor versus thermally prorated section), test procedure (ex.: thermal stability with voltage application after the $W_{th}$ test), waveshape used in the test, etc.

It is also a common misunderstanding, from the manufacturers' as well as of the users' side, that a 100 kA high current impulse has anything to do with a real lightning stress. This may be true for the amplitude, but the time duration of the high-current impulse (shape 4/10 µs) is one to two orders of magnitude shorter than in a real lightning strike.

## 11 Power-frequency voltage-versus-time test rationale

### 11.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages.

### 11.2 Purpose of the test

The purpose of this test is to demonstrate the TOV (temporary overvoltage) withstand capability of the arrester without and with prior duty. In this test, the TOV is strictly a power-frequency overvoltage for time periods from 0,1 s to 3 600 s. See Figure 6.

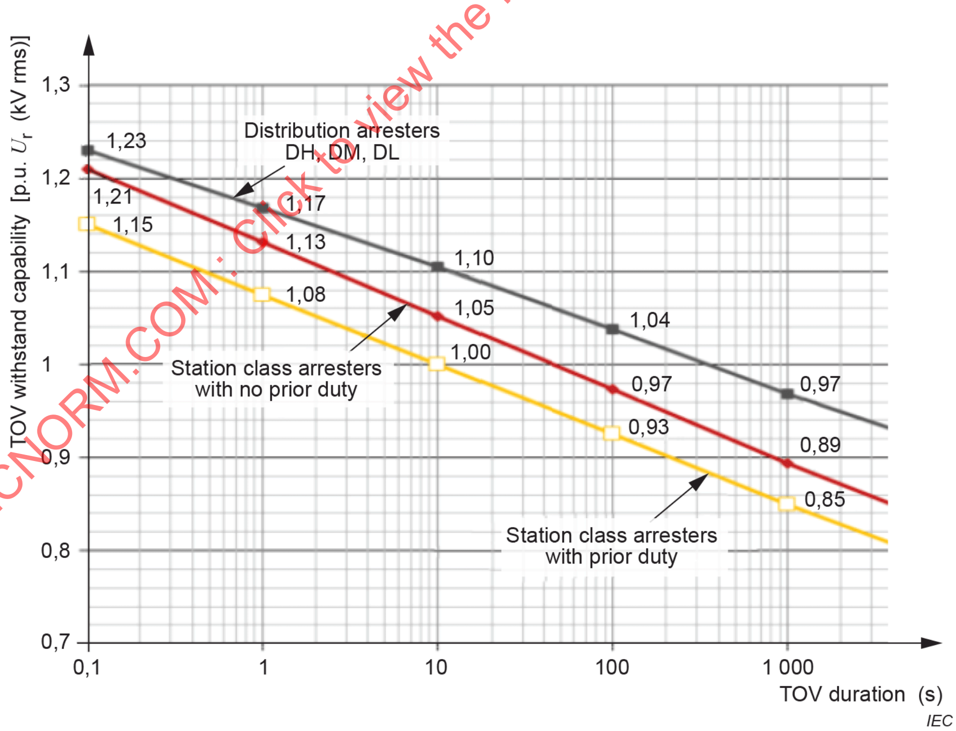



**Figure 6 – Examples of TOV curves**

NOTE These TOV curves are examples only (from ArrestersWorks) and do not show mandated maximum or minimum values except for the 10 second point on the prior duty curve that must be at least equal to $U_r$ of the arrester. Also, note that the prior duty and no prior duty curves may not be parallel with each other, depending on the design.

### 11.3 Historical notes

The concept of a power-frequency voltage vs. time characteristic was introduced in the earliest IEC 60099-4 series. It was unnecessary with gapped SiC arresters that had an inherent power-frequency sparkover level of 1,5 to 2 times the arresters rated voltage and the arresters therefore were immune to system voltage swings. Since MO surge arresters were introduced, the standard has required that a power-frequency versus time characteristic be supplied by all manufacturers of arresters. However, the source of the data could be calculations or historical values from other testing. No tests to validate the published data was required however, if a customer desired such data they could negotiate with the supplier to run a test that was outline in Annex C of all editions prior to 2014 (edition 3).

With the publication of IEC 60099-4:2014, a power frequency versus time curve verification was mandated. This change brought the IEC 60099-4 tests more in line with IEEE C62.11 test requirements. It also standardized prior duty energy injection levels.

### 11.4 Test rationale

#### 11.4.1 General

AC overvoltage events on systems are very common in particular after a fault on the circuit. It is important that arresters are designed to withstand these overvoltage events.

The arrester is tested for both worst case and best-case scenarios therefore both prior duty and not prior duty tests are conducted. This allows the user to interpolate between these two scenarios.

#### 11.4.2 Sample selection rationale

The thermal recovery part of this test is carried out with thermally prorated sections, because the purpose of this part is to demonstrate the thermal stability of the arrester design after an overvoltage event.

The samples are selected in order to represent the most onerous conditions and the samples must result in the maximum heating per unit of MO resistor volume. This is accomplished by using MO resistors with the highest residual voltage per unit length of the design, and minimum $U_{ref}/U_r$ ratio. See IEC 60099-4:2014, Annex K for example of calculating the test voltages.

#### 11.4.3 Test procedure rationale

A graphical representation of the power-frequency versus time test is shown in Figure 7.

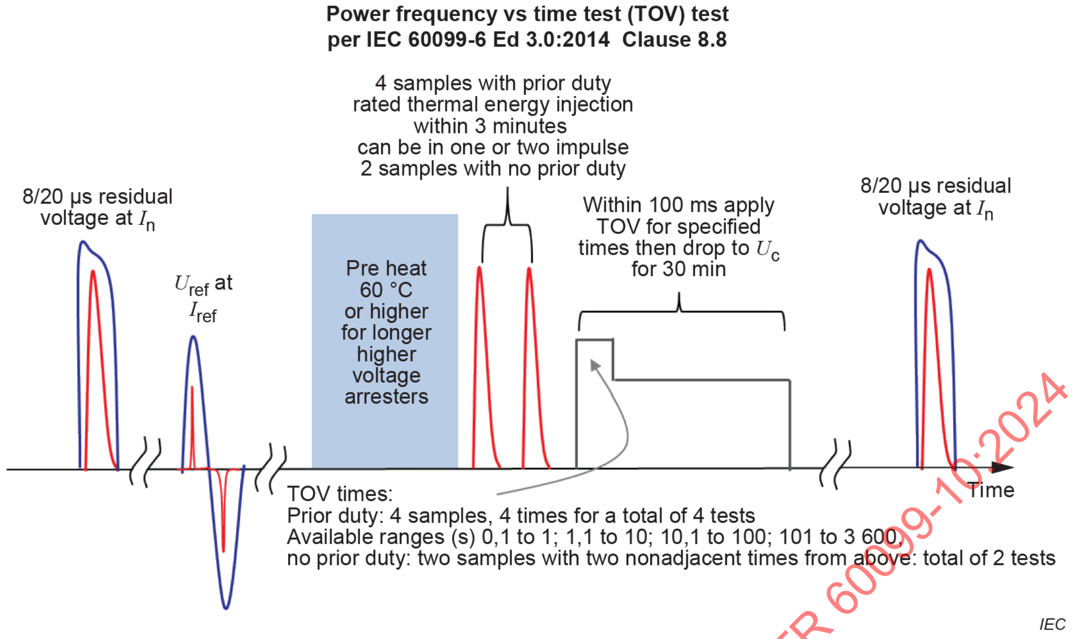



**Figure 7 – Power-frequency versus time test sequence**

The test procedure rationale for the power frequency withstand test is the same as it is for the operating duty test. The only difference is there are no high current (aging) impulses between the initial tests and the preheating for overvoltage test section.

The shorter overvoltage test times represent typical system fault interruption times for grounded systems. The longer overvoltage times represent typical fault interruption times of impedance earthed and unearthed system.

### 11.4.4 Evaluation rationale

The evaluation rationale is the same as the operating duty test rationale, see 10.4.4.

### 11.4.5 Common misunderstandings

At the present time, the above method of verifying an arresters' TOV capability is the only recommended method. Even though $W_{th}$, $Q_{rs}$, and $Q_{th}$ are all charge or energy ratings of the arrester, it is not recommended that these values be used to determine the TOV capability of an arrester.

## 12 Tests of arrester disconnector rationale

### 12.1 Arrester type for which the tests are applicable

These tests apply for all types of arresters installed with a disconnector.

### 12.2 Purpose of the tests

The purpose of the disconnector tests is to verify that the disconnector of an arrester:

- can withstand all stresses related to their application in arresters without operating.
- will perform according to the time-current characteristic published by the manufacturer.

Furthermore, the water tightness and the mechanical strength of the disconnector must be verified (see IEC 60099-4:2014, 6.14).

### 12.3 Historical notes

Disconnector tests were first introduced in IEC 60099-1 for gapped silicon-carbide arresters and were carried over to IEC 60099-4:1991 for MO resistors. Since then, the tests have been expanded to include additional non-electrical stresses (e.g. mechanical and sealing).

### 12.4 Tests rationale

#### 12.4.1 General

The tests of the arrester disconnector include three categories of tests, which are described in 12.4.3. IEC 60099-4:2014 clearly states their purposes, which are described in 12.2.

#### 12.4.2 Sample selection rationale

There is nothing special about sample selection for this test unless the manufacturer has various disconnector ratings. In this case the rating that will be used with the arrester in question should be tested.

#### 12.4.3 Tests procedure rationale

##### 12.4.3.1 Tests to confirm no operation during normal operating conditions

During the life of any arrester, there will be numerous occasions where the arrester serves its purpose and conducts either lightning or other transient currents. It is imperative that the disconnector does not operate during these events. No operation in this sense means that the disconnector does not ignite or separate. Therefore, the disconnector is tested with the same operational duties as those of the arrester to which it is connected.

##### 12.4.3.2 Tests to confirm operation during overload conditions

If an arrester is overloaded, then it is imperative to know the time it takes for it to be disconnected from the system. If the arrester is downstream of a fuse (as may be the case in a distribution application), the disconnector operation time should be coordinated with the fuse operating characteristic. It is of most importance that the disconnector provides a permanent and obvious visual indication of disconnection as well as a sufficiently fast operation to avoid possible reclosure into a short circuit.

##### 12.4.3.3 Mechanical and environmental tests to ensure long operation

In addition to expected electrical stress, the disconnector must also withstand expected mechanical stress during its lifetime. Suitable tests have been designed to offer the user assurance that the disconnector will survive the applicable stresses. The disconnector applied to distribution circuits is not subjected to mechanical stress in the same manner as those of an NGLA and therefore the tests are waived for distribution arresters; although specifics of the application can be agreed between the user and manufacturer.

It is generally accepted that moisture ingress into the active components area of the disconnector can have a negative effect on both the operation and reliability of the device. Based on historical field experience, a seal pumping test is used as a universally recognized method for testing seals of various designs. Through temperature cycling, the test is considered to represent the worst case thermal stress a disconnector will experience in service.

#### 12.4.4 Evaluation rationale

The evaluation of the disconnector during the withstand test is meant to be simple. If it does not operate and disconnect during the stress tests, the sample has passed.

There is no evaluation of the time variable during the time to disconnect tests since there is no defined pass-fail criteria. The manufacturer is only asked to publish the results. It is important to note there that the data published is the moment of ignition of the disconnector. Also note that disconnectors are not current interrupting devices so the only time that can be plotted is the time to operate.

Because the end of the disconnector that remains on the arrester will be energized at system line to ground voltage, it is important that the section of the disconnector that separates from the arrester is far enough away so that flashover does not occur. Hence effective and permanent disconnection is necessary.

Evaluation of the disconnector for the mechanical and environmental tests has been determined so service conditions will not have any negative impact on the performance of the device.

## 13 Short-circuit tests rationale

### 13.1 Arrester type for which the test is applicable

This test applies to all arrester types and voltages. Nevertheless, since this test is under review in MT4 for these types of arresters, separable and dead-front and liquid-immersed arresters are not included yet in the actual document.

### 13.2 Purpose of the test

The purpose of this test is to demonstrate that an arrester failure does not result in a violent shattering of the arrester housing and that any resulting flames are self-extinguishing within a specified period of time.

### 13.3 Historical notes

The short circuit test was introduced to IEC 60099-1 (for gapped SiC arresters) from the very beginning (Edition 1:1958). At that time, it was named "pressure relief test", because only porcelain-housed arresters were available, in which an internal overpressure builds up under short-circuit conditions. Pressure relief classes A through E were used, corresponding to short-circuit currents of 40 kA (Class A) down to 5 kA (Class E). The test had to be performed only on designs with pressure relief measures, leading to a situation that potentially unsafe arresters with no pressure relief devices could be installed on networks without any verification of their short-circuit behavior. In IEC 60099-1:1991, higher short-circuit currents (50 kA, 63 kA, 80 kA) were introduced, but they were not given class names anymore. The test was renamed to "short-circuit test" in IEC 60099-1:1999, which was the last edition of this standard before it was finally withdrawn in 2013. Here for the first time, intermediate high-current levels (approximately 50 % and 25 % of the rated short-circuit current) were introduced, because it had turned out in service that arrester housings may shatter violently at low fault current levels, even if they had passed the short-circuit test at the specified maximum current levels without any problems. By 1990, polymer-housed arresters were entering the market and an appropriate short-circuit test was needed for them since they reacted differently than porcelain-housed arresters to fault current. Up to IEC 60099-4:1998, only a reference to the short-circuit test of IEC 60099-1 was given in the section on requirements. In edition 1.2 (2001) of IEC 60099-4, if a short circuit rating was claimed by the manufacturer, it should be tested according to an informative annex of the standard. This was an unsatisfying situation, because a normative requirement referred to an informative annex for the test procedure. It was not until 2006 that a mandatory short-circuit test procedure was introduced to the standard (IEC 60099-4:2006). Here for the first-time, different basic designs ("Design A", "Design B") with regards to the amount of internal gas volume and the typical expected failure mode was introduced.

## 13.4 Test rationale

### 13.4.1 General

Short circuit tests are destructive overload tests performed to show that an arrester failure does not result in a violent shattering of the arrester housing or any components potentially causing injury to personnel or damage to valuable assets. In addition, it must be demonstrated that all flames are self-extinguished within 2 minutes to verify this property.

This test is performed in high current laboratories and is meant to simulate in service conditions. All arrester types are tested with four current levels. One high current, one low current and two intermediate current levels. The reason for the intermediate current levels is that arresters behave differently for different internal pressures (current levels) which may lead to longer time for opening/venting of the arrester housing. The longer time the arc stays inside the arrester without opening/venting, the higher the risk for a more violent failure mode of the arrester.

Short circuit tests on surge arresters are single point tests, which do not involve additional statistical evidence. Destructive tests on other HV equipment follow a similar approach and do not require a statistical evidence (e.g. internal arc test, internal pressure test). However, the four current levels already constitute a significant statistical quantity for assessing the operation under such conditions in the field as well as the validity of the test evaluation statement and the verification of the safe failure mode. Another contributing factor to the single point testing principle is the field experience, where failed surge arresters have shown similar external signs as the samples used in short-circuit tests in the laboratories. In addition, the fact that several manufacturers produce and type-test arresters of similar designs (e.g. same mechanical concept for a surge arrester of SL, SM and SH class) contributes to the sufficient statistical verification of its performance. Finally, minor design changes through the product lifetime and/or customer requests for test repetitions may also be considered a statistical reconfirmation.

There are two fundamentally different types of arrester design, designated as "Design A" and "Design B", requiring different test procedures due to their short-circuit current performance.

Design A arresters have internal gas channels that occupy more than 50 % of the total internal volume. Overloading of such arresters will typically cause high stresses in the gas channel, which may result in complete dielectric breakdown of the gas channel. These arresters typically have pressure relief devices to quickly vent the built-up pressure from the resulting short-circuit arc to prevent the internal pressure from reaching a level that could cause violent scattering of the housing.

Design B arresters have MO resistor stacks that have no significant exposure to gas. The MO resistors are typically contained in a cage or wrap of FRP (fiber-reinforced plastic) material that is subsequently overmolded with or inserted into a housing made of organic material. Overloading of such arresters will typically result in dielectric failure through the body of the MO resistors or along the MO resistor stack surface within the cage or wrap. The built-up pressure can vent anywhere along the housing or through designated weaker parts of the housing.

Motivation for defining "Design A" and "Design B" was that in case of a breakdown/flashover in the gas channel, the arc will develop very quickly over the entire length of the arrester. This may generate an intensive shock wave in the gas channel, stressing the housing over its entire length and imposing high requirements on pressure relief devices to open quickly. Furthermore, the probability of an asymmetric current is high with this flashover mechanism.

In case of a breakdown in the solid material, the arc will develop more slowly, and the probability of an asymmetric short-circuit current is low. Thus "Design A" defines an arrester where the probability of a failure initiated in the gas volume is much higher than in the solid material, and "Design B" defines a design with a higher probability of failure initiated in the solid material. Accordingly, the mode of short-circuit initiation is different for these two designs.

One notable change that occurred with the 2006, edition 2.1 (2006) is that the first half-cycle fault-current asymmetry is not required for polymer housings with no appreciable internal gas volume. This is predicated on results of tests reported by Smeets et-al, in which it was found that the rate of energy input into the arc, still internal to the arrester just after the short-circuit initiation, is much faster with symmetrical current than with asymmetrical current. It is assessed that testing with the symmetrical current and higher rate of energy input imposes more severe duty on polymer-housed arresters of Design B than does the asymmetrical current.

The rated short circuit magnitudes from 5 kA to 80 kA correspond to values that are contained in the R10 series specified in IEC 60059.

The time duration requirement for the high current tests and reduced current tests is at least 0,2 s. This duration is assumed to be based on average transmission system fault clearing time. Field experience shows that arresters normally fail safely on networks even where longer fault clearing times exist, such as may occur on distribution systems, likely because venting occurs well before 0,2 s.

The time duration requirement for the low current test is at least 1,0 s for design B arresters or until it vents for Design A arresters. This relatively long-time requirement is to ensure that the venting systems operate at these low currents.

### 13.4.2 Sample selection rationale

For porcelain-housed arresters and polymer-housed arresters with composite hollow insulator ("Design A" arresters), it is generally agreed that a fuse wire in the gas volume to initiate the short-circuit along the surface of the resistor column represents the most relevant failure scenario.

For polymer-housed arresters with housing directly applied onto the varistors ("Design B" arresters), a fuse wire along the varistor surface cannot be accepted because the test would be unrealistically easy to pass. On the other hand, a fuse wire through holes drilled through the varistors is a too harsh scenario, as it can hardly be imagined that all varistors of a failing arrester will break by puncture. It is therefore justified to specify a pre-failing method, as the most reasonable compromise with regards to test severity and realism.

An exception had to be made only for porcelain-housed arresters of "Design B," where the pre-failing method could cause less severe test conditions (in case the arc develops in the gas channel and not in the solid material as originally intended), a risk that can be accepted for polymer housings but not for housings of brittle material.

Any length sample can be used for the low current tests. The rationale behind this is that the primary purpose of the low current test is to test the positive operation of the venting system. It is understood that the length of the sample may affect this test result, but at the time it was written, it was assumed that the effect is not substantial.



### 13.4.3 Test procedure rationale

A typical arrester failure in the form of an internal short-circuit will start with the breakdown of one MO resistor, which will progress to a total breakdown of the total arrester stack either by flashover external to the MO resistors but inside the arrester housing or by a breakdown within the body of the MO resistor stack. The mode of failure will typically be dependent on the mechanical design of the arrester, namely Design A or Design B.

In laboratory tests of Design A arresters, this mode of failure can be simulated by preparing the test samples with a fuse wire along the MO resistor stack, within the gas channel from one end of the arrester to the other.

In short-circuit testing of Design B arresters, it has been shown that use of a fuse wire, such as in Design A arresters, leads to a rather benign result that does not simulate what is observed with field failures of such arresters. To better represent the observed field failure mode in typical, short-circuit test laboratories, it has been found that it is necessary to reduce the resistance of the MO resistors prior to the connection of the source of the power-frequency short-circuit current. This is accomplished by applying a power-frequency overvoltage until the resistance has reached a level that will allow the generator to maintain the required short circuit current through the sample. This state is presumed to have been attained when the voltage across the sample during the pre-heating has fallen to less than 10 % of the originally applied voltage.

Per 10.8.10.4.3 of IEC 60099-4:2014, a re-prefail procedure can be carried out on samples that have recovered a withstand capability to a level higher than the high current generator can overcome. This re-prefail method was developed specifically where the test laboratory needs more time to install the arrester in the short circuit test fixture. The maximum amount of charge that can be applied for this second prefail test is 60 As. (Note there is an error in the caption of Figure 10 that states a maximum of 30 A is allowed, where it can be 300 A if the time is 0,2 second, which yields 60 As).

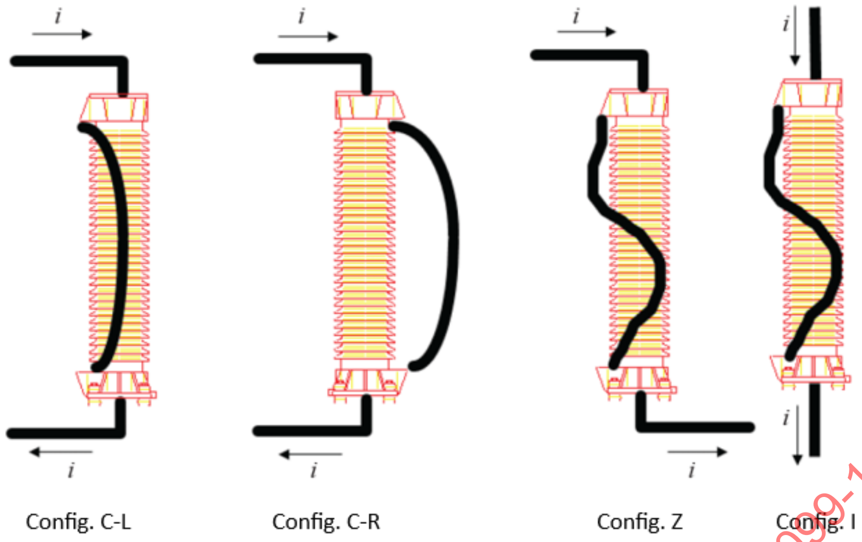
Per 10.8.10.2.3 of IEC 60099-4:2014, no physical modifications shall be made to the sample between the pre-fail test and the short circuit test. Based on the latest discussion on this topic by this working group, this means that the sample shall not be modified by personnel, but if the sample was deformed during the pre-fail test, that is acceptable as long as it does not fall off the stand.

The reason the mounting arrangement is specified is to ensure the failure mode is as realistic as possible and represent all possible service conditions.

The platform is mounted off the floor so that there is room to secure the lead in the direction for worst case failure mode. The platform is insulated so that it does not represent a ground plane where the arc can land away from the arrester.

The purpose of the enclosure is to collect parts that fall roughly straight down, not to contain parts from a violently shattering arrester. Prior to edition 2.1 (2014), the enclosure had a radius equal to the height of the arrester. This was changed due to experience of parts falling to the floor and bouncing over the enclosure. Since a reflected part off the table hardly counted as a failure, the radius of the circle was increased to 1,2 times the height of the arrester.

The direction of the leads is specified because certain configurations do not represent the worst-case failure scenario. Movement of the power-frequency arc is affected by the electro-dynamic forces originating from the connecting leads. Depending on the design of the test sample, different ways of arc movement will constitute worst case conditions to pass the test. For example, in a porcelain housing, it is most unfavorable if the internally burning arc is accelerated away from the vents, and for polymer housed arresters an arc that stands still may ignite a fire on the housing. Exemplary worst cases dependent on arrester design and routing of the connecting leads are listed in Figure 8.




| Insulation | Config. C-L | Config. C-R | Config. Z | Config. I |
|---|---|---|---|---|
| **Porcelain** | Worst case | Most favorable case | Neutral cases | |
| **Polymer design A** | Favorable factor | Most favorable case | Worst cases | |
| **Polymer design B** | Most favorable cases | | Worst cases | |

**Figure 8 – Impact of the connecting leads on arc movement and short-circuit test severity**



### 13.4.4 Evaluation rationale

The fundamental criterion for successfully passing the tests remains as in earlier version of this test, in that the arrester shall not fail in a violent manner. In earlier versions, no fragments were allowed but it has turned out that allowing absolutely no parts to be found outside the enclosure is a too severe requirement. It is very likely that even in a successful short-circuit test, small parts of the test sample, which due to their limited kinetic energy, are probably not dangerous to personnel, will find their way outside the enclosure, either directly or by deflection from the floor inside the enclosure with a successive jump over the border. Though this has in general to be considered a favorable short-circuit behavior (in case of an explosion, heavy arrester parts would easily be expelled over a distance of several meters), such cases consistently cause endless discussions on the test result. Following the lead taken in IEC 62271-200, the current evaluation procedure, therefore, permits solid fragments (e.g. metal parts, MO resistor parts, etc) of less than 60 g each to fall outside the enclosure. Soft parts of polymeric material, diaphragms and vent covers are permitted to fall outside the enclosure because they are considered likely not to cause significant damage.

IEC 62271-200 for high voltage switchgear explicitly deals with internal arc testing with respect to the safety of personnel and public in case of failures within substations. Two levels of accessibility have been adopted, where the accessibility B refers to stations that are directly accessible to the public. Although these standards deal with the safety of persons and are, therefore very restrictive concerning possibly arising danger, they permit projection of parts out of the station up to a weight of 60 g each as compared to the value of 10 g specified in IEC 60099-4:2004 (Edition 2). Furthermore, it would be of advantage if all standards dealing with similar parts of a power system specify similar requirements. Therefore, it was decided that the permitted value of 60 g per projected part is also adopted for the short-circuit testing of surge arresters.

#### 13.4.5 Common misunderstandings

The name of this test could be somewhat misleading due to the comparison with short-circuit ratings and tests of other HV equipment (such as breakers, transformers, cables), which shall remain fully functional after their respective short-circuit test.

## 14 Test of the bending moment of porcelain-housed arresters rationale

### 14.1 Arrester type for which the test is applicable

This test applies to all porcelain and cast-resin housed arresters above $U_s$ = 52 kV as well as all porcelain and cast resin housed arresters at system voltages below or equal to 52 kV, for which the manufacturer claims cantilever strength per IEC 60099-4. Also note that polymer housed arresters are covered in Clause 15. Other types of arresters are not covered by this test because the procedures would not apply in most cases or cantilever strength is not specified.

Cast resin housings are included in this section even though they do not behave exactly like porcelain housings, but their brittleness is much more like porcelain rather than flexible polymers.

Bending moment tests of insulating bases and brackets are covered in a subclause of this test for the case they are not an integral part of the arrester and various models can be used with a specific arrester. Testing the base/bracket at this point would lead to redundant tests with only minor variations that are not relevant to this objective.

### 14.2 Purpose of the test

This test demonstrates the ability of the arrester to withstand the manufacturer's declared values for bending loads. The standard only specifies the test procedures. Because there are so many different applications of arresters, bending load levels are not mandated by the standard.

### 14.3 Historical notes

German Standard DIN 48113:1973-09 provides the basis of MBL, SSL and SLL for porcelain housings. The relationships of the three parameters, as shown in Figure 9, result from the brittle nature of porcelain with a large variety of individual values.

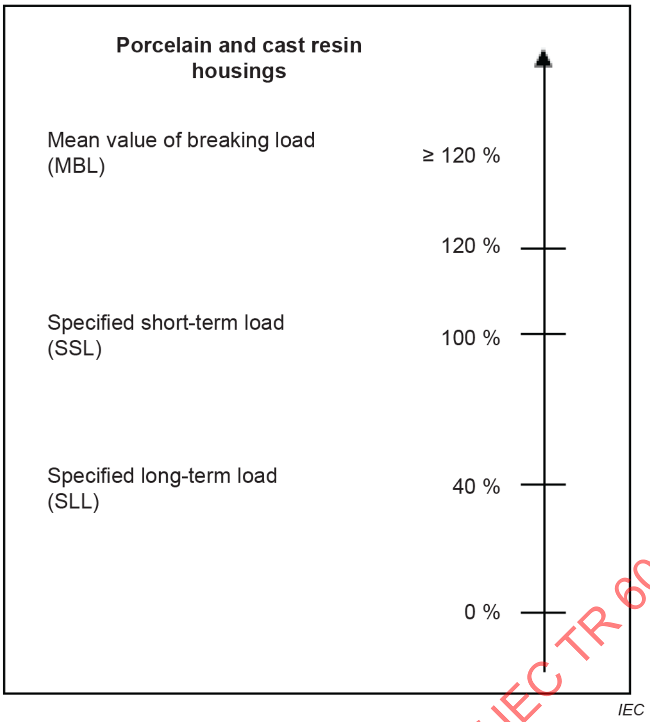



**Figure 9 – Graphic representation of the relationships between tests in the bending moment tests for porcelain-housed arresters**



The critical relationship is that MBL must be 20 % higher than SSL. Therefore, MBL must be tested to calculate SSL.

Following the guidelines of DIN standard 48113-1973-09, SLL is defined as 40 % of SSL and based on practical experience is considered to be a safe continuous load on porcelain housed or cast resin housed arresters.

IEC 60099-4:2001 covered mechanical testing for the first time, with requirements for porcelain and polymer housed arresters included in one section of the standard.

Then, in IEC 60099-4:2004, mechanical tests for porcelain and polymer housed arresters were separated into two different clauses.

The main reason for improving this test series in IEC 60099-4 was that the test procedures and acceptance criteria for polymer-housed arresters were criticized as not being relevant and not taking into account the different mechanical behaviors of polymer-housed arresters.

Regarding porcelain and cast-resin housed arresters, considering the long service experience, the introduction of a new cyclic test for this arrester design was not considered necessary.

### 14.4 Test rationale

#### 14.4.1 General

Porcelain and cast resin housings are tested differently from polymer housed arresters. Mean Breaking Load (MBL), Specified Short-Term Load (SSL), and Specified Long-Term Load (SLL) are all considered in this section. Tests are specified for MBL and SSL with the requirement that MBL shall be at least 20 % higher than SSL. Since the SSL test demonstrates that the sealing and the internal parts of the arresters are not affected by a bending load at SSL, SLL is not tested, and it is presumed that the arrester will withstand this bending value on a long term basis as specified by the original DIN 48113:1973-09 definition and then by IEC standards, IEC 62155 among others.

### 14.4.2 Sample selection rationale

Because of the nature of the porcelain and cast resin housing, an MBL test on a single sample may result in an unusually high or low result. For this reason, three samples are specified for the test.

To simulate field installation, one end of the sample shall be firmly fixed to a rigid mounting surface of the test equipment and a load shall be applied to the other (free) end of the sample to produce the required bending moment at the fixed end. Because it is possible in service to have loads applied in any given direction, the weakest direction of the arrester must be tested.

NOTE The MBL test is an assessment of the housing only and internal components may be excluded as part of the sample because internal components cannot affect the MBL of the housing. On the other hand, the SSL test samples must contain internal components to have full functionality of a complete arrester.

### 14.4.3 Test procedure rationale

The time durations used in the procedure of the MBL test come from IEC 62155 and are based on practical experience for many years. Figure 10 shows examples of MBL and SSL test results.

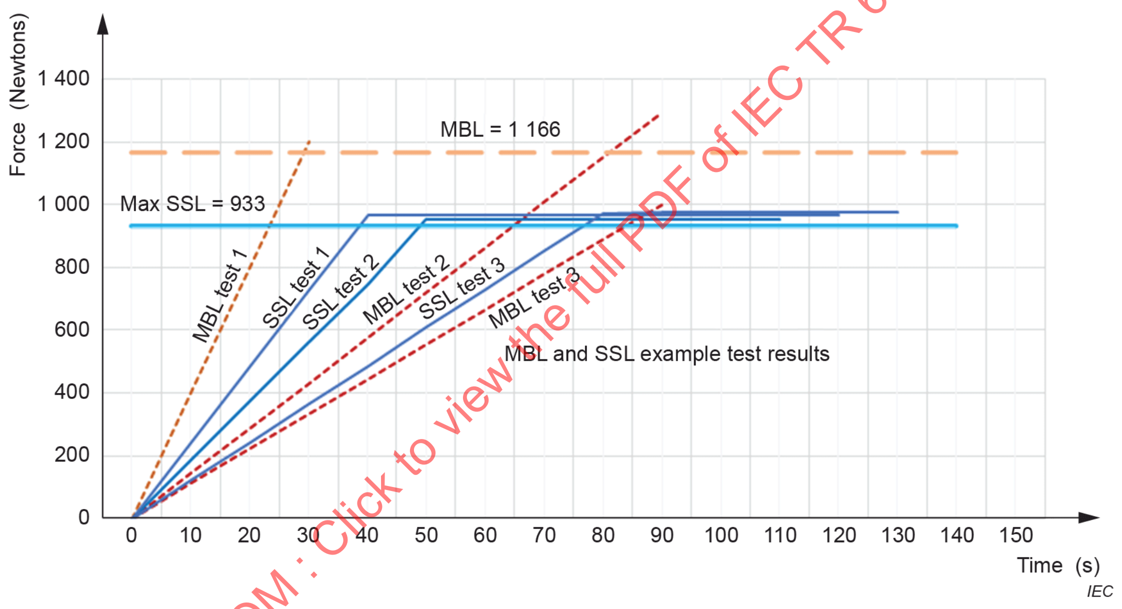



Figure 10 – Examples of MBL and SSL test results

This is a new test for arresters, though not a new concept. It was defined in the past, but there was not a definition of breaking load. This test and value pertain only to brittle arresters such as porcelain housed and cast resin housed arresters. The test needs to be watched closely for the first sign of damage, which may not be obvious.

The time durations specified for the increase to SSL and hold of the load at SSL also come from IEC 62155 and also from practical experience.

### 14.4.4 Evaluation rationale

The MBL test is performed to establish the basis of SSL and per the standard, MBL must be ≥ 1,2 × SSL.

The SSL test verifies that the sample can withstand the specified short-term load without damage that would affect the performance of the arrester. The verification is realized by the mechanical test followed by a visual examination, a check of permanent deflection, a leakage seal test and a partial discharge test that may be affected by a failure of the sample. The leakage test and partial discharge test are considered to be more sensitive than a physical examination.

## 15 Test of the bending moment of polymer-housed arresters rationale

### 15.1 Arrester type for which the test is applicable

This test applies to polymer (except cast-resin) housed arresters (with and without enclosed gas volume) for $U_s$ > 52 kV. It also applies to polymer (except cast-resin) housed arresters for $U_s$ ≤ 52 kV for which the manufacturer claims cantilever strength.

Bending moment tests of insulating bases and brackets are covered in IEC 60099-4:2014, 8.11 for the case where they are not an integral part of the arrester and various models can be used with the arrester. Testing the base/bracket at this point would lead to redundant tests with only minor variations that are not relevant to this objective. See Figure 11.

### 15.2 Purpose of the test

As for porcelain housed arresters, this test demonstrates the ability of the arrester to withstand the manufacturer's declared values for bending load. The standard only specifies the test procedures. Because there are so many different applications of arresters, bending load levels are not mandated by the standard.

Because of their design and the way the end fitting are installed, polymer housed arresters and especially those without tubes and according to design B, shall be subjected to the terminal torque preconditioning according to 10.8.12.3.1.1, the thermal preconditioning according to 10.8.11.3.1.3 and the water immersion test according to 10.8.11.3.2 of IEC 60099-4:2014 even when there is no declared values of bending moment.



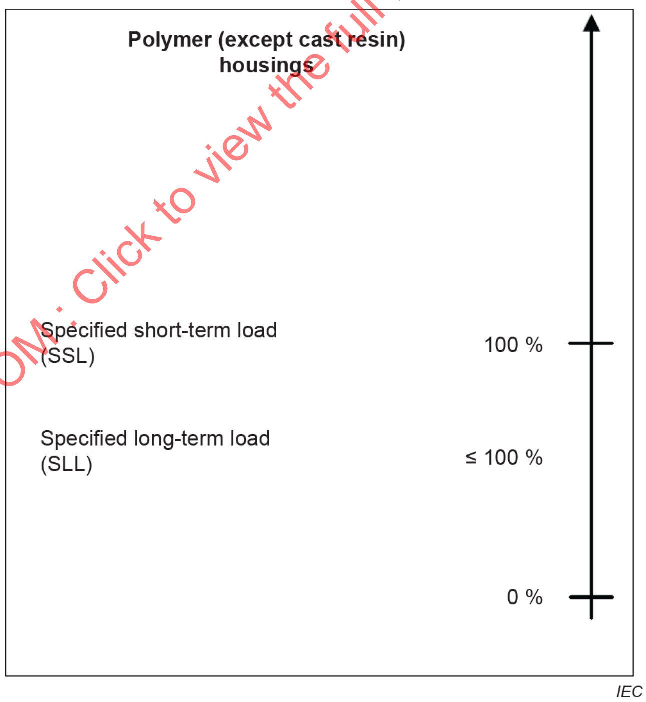



**Figure 11 – Graphic representation of the relationships between tests in the bending moment tests for polymer-housed arresters**

### 15.3 Historical notes

IEC 60099-4:2001 covered mechanical testing for the first time, with requirements for porcelain and polymer housed arresters included in one section of the standard.

Then, in IEC 60099-4:2004, mechanical tests for porcelain and polymer housed arresters were separated into two different clauses.

The main reason for improving this test in IEC 60099-4 was that the test procedures and acceptance criteria for polymer-housed arresters were criticized as not being relevant and not taking into account the different mechanical behaviors of polymer-housed arresters.

Polymer arresters historically have lacked similar common rules for the definition of dynamic and static service loads, which strongly depend on the arrester design. Of specific interest is the performance of polymer arresters under continuous loading of a cyclical nature. Due to their construction, in contrast to stiff porcelain-housings, polymer arresters of all designs may flex under bending load. When this is repeated cyclically, it may be the primary factor, which determines the true limit of permissible bending moment that can be applied. In order to consider potential effects of "mechanical ageing", SLL and SSL are therefore not explicitly related by a fixed factor for polymer-housed arresters, and instead bending moment loads are evaluated based on their interdependence as defined by the arrester manufacturer. Furthermore, since polymer-housed arrester will safely go into plastic deformation well before physically breaking, there is not a ratio, nor requirement, to define MBL either.

## 15.4 Test rationale

### 15.4.1 General

Polymer arresters have historically lacked common rules for the definition of dynamic and static service loads, which strongly depend on the arrester design. If potential effects of "mechanical ageing" during continuous loading are not considered, load levels may be chosen at very high levels compared to what the arrester design can actually handle. In other words, the short-term bending moment level could be set just a little below the breaking load. However, it is doubtful whether the arrester would handle these high mechanical loads at the given load levels (continuous and short-term) under actual conditions during its service lifetime.

Of specific interest is the performance of polymer arresters under continuous cantilever loading of a cyclical nature. Due to their construction, polymer arresters of all designs may flex under bending load and, when this is repeated cyclically (as would occur over their service lifetime), this may be the primary factor which determines the true limit of permissible bending moment. A specified short-term load verified on new arresters not previously subjected to any tests may thus give a too optimistic value.

Subjecting the arrester, in a cyclic way, the continuous bending load may result in significant remaining permanent deflection which in turn, may affect the likelihood of moisture ingress and/or jeopardise the mechanical integrity of the housing and/or MO resistors causing electrical malfunction. Additionally, insulation withstand clearances to other equipment may be compromised if the deflection is extreme. Furthermore, the maximum short-term load that can be applied without breaking may be significantly reduced after the arrester has been subjected to a continuous load in a cyclic manner. Hence, a test is required to verify that an arrester, even after many years in service and having potentially been mechanically fatigued, can both remain functional and sealed as well as still be capable of withstanding a serious mechanical incident that occurs, for example a short circuit or earthquake.

### 15.4.2 Sample selection rationale

Because bending loads could affect the sealing system as well as the internal parts of the arrester, the test samples shall contain the internal parts. Initial electrical measurements are made before the test for comparison in the test evaluation.

As for porcelain housed arresters, the samples are firmly fixed to a rigid mounting surface to simulate field installation.

There is a minimum arrester unit length that must be used in order to test the housing and not only the flanges and the fitting between the flanges and the housing. This length is at least as long as the greater of:

- 800 mm.
- three times the outside diameter of the housing (excluding the sheds) at the point it enters the end fittings.

It is based on IEC 61462:2007, 7.2.1 and can also be found today in IEC 62772:2016, 8.2.2.

### 15.4.3 Test procedure rationale

One thousand has been chosen as a reasonable and sufficient number of cycles to test the arrester ability to sustain the bending load over a lifetime. Damage is typically seen in the early stage of a few hundred cycles if ever a too high value of SLL is chosen for a specific arrester.

The procedure in IEC 60099-4:2014, Figure G.5 is a combined moisture ingress and bending moment test from IEC 60099-4 (which were separate tests up to 2006 (edition 2.1). Number of samples for the different steps were chosen in order to have a reasonable compromise regarding the cost and duration of such test.

Standard IEC 61462:2007 states that the temperature variation for such a test must be at least 85 K. Sequence from Figure 11 of 60099-4:2014 was chosen to respect this 85 K minimum and to cover the whole span of housing temperatures in IEC 60099-4 (both min and max values), which is from −40 °C (minimum ambient temperature) to +60 °C (+40 °C ambient +20 °C housing heating).

Water salinity and duration of water immersion test come from IEC 62217.

### 15.4.4 Evaluation rationale

If the arrester passes 1 000 cycles at the SLL and subsequent water immersion and evaluation tests, it is considered likely that the arrester can continuously be subjected to the SLL. Furthermore, the test validates that the SSL is a load which the arrester could be subjected to even after many years in service. For short polymer arresters, i.e. arresters for system voltages not exceeding 52 kV, a cyclic load test has not been considered necessary as the applied bending moment in service is deemed negligible on shorter arresters.

## 16 Environmental tests rationale

### 16.1 Arrester type for which the tests are applicable

The tests are applicable only for arresters with porcelain housings and cast resin housings. For polymer-housed arresters, it is considered that the weather ageing test imposes sufficient environmental stress, and hence no additional tests are needed on these types of arresters.

### 16.2 Purpose of the tests

The purpose of the tests is to demonstrate that the arrester sealing system is not adversely affected by exposure to environmental stresses. The tests are intended to show that the arrester will remain immune to moisture ingress over its service life.

## 16.3 Historical notes

Environmental tests were first introduced in IEC 60099-4:2004. Three specific tests were specified:

- a temperature cycling test, based on tests of IEC 60068-2-11:1981.
- a sulphur dioxide test, based on tests of IEC 60068-2-42:2003.
- a salt mist test, based on tests of IEC 60068-2-11:1981.

Polymer housed arresters were originally required to be subjected to the same environmental tests, but the requirement was removed in IEC 60099-4:2009 with the introduction of an expanded bending moment test for polymer-housed arresters that included a combination of mechanical loading and environmental exposure that were considered sufficiently stressful to assess the integrity of the sealing system.

Also, the sulphur dioxide test, which had the purpose of ageing the metallic parts and contacts of both porcelain housed (included cast resin) and polymer housed arresters, was removed in IEC 60099-4:2009, having been judged to be a time consuming test that did not provide useful information.

## 16.4 Test rationale

### 16.4.1 General

These tests focus on two major environmental conditions that could lead to failures of the arrester's sealing system, namely temperature cycling (which could result in expansion and contraction of sealing components) and also exposure to saline pollution (which could cause severe corrosion on metals or chemical reaction on parts of the sealing system).

### 16.4.2 Sample selection rationale

The tests are intended to evaluate the effect of environmental stresses on the integrity of the arrester sealing system, for which the length of the arrester housing and the arrester internal parts have no influence on the result of the test. For this reason, and practical considerations for the test arrangements, an arrester unit of any length can be chosen, as long as the sealing system and the materials are the same for all arrester units of the same type.

### 16.4.3 Test procedure rationale

To verify that the stresses do not impair the sealing system, a routine seal check (IEC 60099-4:2014, 9.1) is required to demonstrate that the unit under test is properly sealed before exposure to the environmental stresses.

The subsequent temperature cycling and salt mist portions of the test are performed to apply stresses that are considered of sufficient intensity to reflect lifetime exposure of the arrester to a normal environment.

A second routine seal check is then performed to check if the applied environmental stresses caused any change in the integrity of sealing system.

### 16.4.4 Evaluation rationale

If the leakage rate of the second seal leak check remains within the limits allowed in IEC 60099-4:2014, 9.1, it is judged that the sealing system will withstand the environmental stresses that the arrester will experience during its service life.