

MODERN ZNO SURGE ARRESTERS UNDER SHORT-CIRCUIT CURRENT STRESSES: TEST EXPERIENCES AND CRITICAL REVIEW OF THE IEC STANDARD

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1. INTRODUCTION

In general, modern surge arresters utilizing ZnO blocks are very reliable apparatus with a low failure rate. A published number for distribution type arresters is 0.1 % failures per year [1], [2], while for high-voltage arresters the estimated failure rate is even lower. However, since the primary duty of the arrester is to protect other equipment under all circumstances a slightly higher risk of failure compared to other apparatus is generally accepted. The philosophy has been that if something goes wrong the arresters should fail first, thereby saving other, more expensive, equipment from damage. Nevertheless, both among manufacturers and users, it is considered extremely important to ensure that the arresters fail in a “safe” way when overloaded. This is also reflected in the standardization work where large efforts have been made on test procedures for pressure relief i.e. short-circuit tests. When polymer-housed surge arresters were first introduced on the market, the manufacturer immediately claimed a better short-circuit performance compared with porcelain-housed arresters. This was due to the fact that the new type of arrester was lacking enclosed gas volumes as well as a housing comprising a brittle material like porcelain. It was thus considered that no explosions with a dangerous scattering of material were possible.

Subsequently it was realized, both by manufacturers and users alike, that special precautions were also necessary for arresters with polymer housings to avoid explosive behaviour under short-circuit.

2 DESIGNS OF POLYMER HOUSED ARRESTERS

The soft outer insulator for polymer-housed arresters does not have the necessary mechanical strength to keep the ZnO column together. Therefore, other insulator material must be used in the design. The most common material used for this purpose is glass fibre reinforced plastic.

There are then several types of mechanical designs in common use: loops, rods, cross windings and tubes. These designs can be grouped generally into three basic categories:

- Open or cage design, referred to as type B2 in the IEC standard [3].
- Closed design, referred to as type B1 in the IEC standard [3].
- Tubular design, referred to as type A in the IEC standard [3].

2a Open (cage) design (type B2)

This design may consist of loops of glass-fibre, a cage of glass-fibre weave or glass-fibre rods around

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the block column. What defines this type of design is that the active components are not fully enclosed by hard materials. Instead, a body of soft polymer material directly surrounds the internal components. An outer insulator with sheds is required over the inner body, with two common methods for achieving this being:

- A pre-moulded polymer insulator is made in a separate process, and then slipped over the internal component assembly (which itself may be enclosed in soft polymer). The boundary between the internal assembly and the outer polymer insulator is usually filled with grease or gel, generally of silicone.
- The outer housing is moulded directly onto the internal components to form a void-free, sealed housing along the entire length of the insulator.

Such designs lack enclosed gas volume. Should the arrester be stressed in excess of its design capability, an internal arc will be established. Due to the open design, the arc will tear or burn its way through the polymer material, permitting the arc, along with any resultant gases, to escape quickly and directly. Hence, special pressure relief vents or diaphragms are not required for this type of design. It is of great importance that no air pockets are present in these designs, otherwise partial discharges might occur, which would lead to the destruction of the insulator over time.

Penetration of water and moisture must also be prevented, which places strict requirements on the sealing of the insulator at the metallic flanges (in the case of a pre-moulded housing) and adherence or bonding of the rubber to all internal parts (in the case where the polymer is directly moulded onto the inner body).

2b Closed design (type B1)

Surge arresters in this category incorporate a “void-free” (partial or total) polymer housing around the internal assembly, while surrounding the active components themselves with hard material. In contrast to the open design, they have been mechanically designed to not include a direct path for externalising the arc during internal short circuit. Typical designs include a glass-fibre weave (wrap) wound directly on the block column or a separate tube in which the ZnO blocks are mounted. A soft polymer insulator is then fitted (either pre-moulded or directly moulded) over this internal component assembly; often together with grease or gel to fill the interfaces.

In order to obtain a good mechanical strength, the weave/tube must be made sufficiently strong, which, in turn, might lead to a too strong design with respect to short-circuit strength. The internal overpressure could rise in the tube design to a high value before cracking the tube, which may lead to an explosive failure with parts being thrown over a wide area. To prevent a violent shattering of the housing, a variety of work-around solutions have been utilized, e.g. slots in the tube. When glass-fibre weave is used, an alternative has been to arrange the windings in a special manner to obtain weaknesses that may crack. These weaknesses are intended to ensure a pressure relief and commutation of the internal arc to the outside; thus preventing an explosion.

Note that such alterations do not then make these an “open design”, as the arc path is not considered to be direct and the internal components are still, in practical terms, surrounded by hard material.

Sealing and partial discharge issues also require consideration in a similar manner as for the open or cage design.

2c Tubular design (type A)

The tubular design incorporates a distinct annular gas-gap between the active parts and the external insulator. It is designed in more or less the same way as a standard porcelain arrester, but with the porcelain housing having been substituted by an insulator of a glass-fibre reinforced plastic tube, moulded with an outer insulator of silicone or EPDM rubber.

The internal parts are, in general, almost identical to those used in an arrester with porcelain housing.

The arrester therefore obviously must be equipped with some type of sealing and pressure relief devices, similar to what is used on porcelain-housed arresters.

This design has the prime advantage that high mechanical strength is possible (potentially even higher than for porcelain). Among the disadvantages compared to other polymeric designs is less efficient cooling of the ZnO blocks and, if appropriate precautions are not taken in the design, an increased risk of exposure of the polymeric material to corona that may occur between the inner wall of the insulator and the block column during external pollution.

The strength and fastening of the flanges to the tube are of major importance with respect to short-circuit performance. The presence of a considerable amount of organic material could increase the internal pressure during short-circuit compared with a porcelain design.

3. POSSIBLE FAILURE MODES

As mentioned earlier, the failure of an arrester is not a common event. However, possible reasons for failure of an arrester include the following:

- Overloading of the active elements by energy or current.
- Moisture ingress.
- Partial flashover of one or several units in a multiunit arrester caused by external pollution, birds or high overvoltages.
- Thermal instability due to the effect of heavy external pollution.
- High temporary overvoltages
- Damage of some blocks in one or several units due to energy and current discharges which leads to power frequency overload of the remaining part of the arrester.
- Mechanical overloading which leads to an electrical failure

Failure during impulse passage may occur due to overloading or quality problems such as significant inhomogeneities in the ZnO blocks, poor electrode adhesion to the material, insufficient surface insulation, etc.

Instantaneous overloading may result in puncture, cracking or flashover of the ZnO blocks. For porcelain housed arrester or a tubular polymer-housed arrester this most probably would result in an internal flashover along the block column. Therefore, in general no redundancy exists i.e. if one block fails it is likely that a complete internal flashover occurs almost instantaneously. In contrast, when one or only a few of the blocks fail in a polymer-housed arrester without internal gas volume, a complete external flashover will be prevented or delayed by the solid insulation material on the surfaces of the ZnO blocks. Thus, some redundancy exists in this type of arrester. This may then result in a power frequency overloading of the remaining part of the arrester, which after some time leads to a complete failure. For arresters with many series-connected blocks the probability of an instantaneous short-circuit is thus less than, for example, a distribution type arrester.

4. SHORT-CIRCUIT TESTING ISSUES

A very important test for the surge arrester is the short-circuit test (formerly referred to in the IEC standard as "pressure relief test"). Hereby, conditions are created in which an internal short-circuit is forced by suitable pre-conditioning (see below).

As shortly as possible after initiation of an (internal) fault arc in the arrester body, pressure rise that might cause explosion must be mitigated by suitable pressure relief measures. This is explained in fig. 1, showing the expulsion of the high-current arc outside of the arrester by a venting system at both terminals of the device. In case no special venting outlets are built-in, the venting is through the polymer housing, as seen in fig. 2.

IEC describes that the arrester passes the short-circuit tests if:

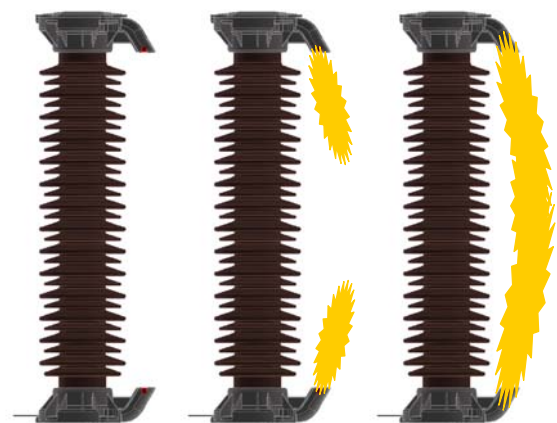


Fig 1. Operating principle of porcelain and tubular design. Left: Arrester in its healthy state. Middle: Arrester has failed short-circuit, pressure relief plates open and gas begins to be expelled through the venting ducts. Right: The two gas streams meet and the internal arc is commutated safely to the outside. This must normally occur before the first peak of current approx. within 5 - 10 ms.

- there are no ceramic (ZnO, porcelain) fragments heavier than 10 g expelled outside a defined circumference around the arrester;
- the arrester must be able to self extinguish flames within 2 minutes.

4a. Standardisation status

During the last decade the standardized test procedures have been made more strict and complete. The test set-up, which has a great influence, has been better defined as well as the way to initiate the short-circuit within the arrester. In addition, a porcelain-housed design must now be tested at several current levels i.e. 100, 50 and 25 % of rated short-circuit current [3]. This prevents “grey zones”, whereby an arrester is designed for only the rated short-circuit current but fails in an explosive way at lower currents.

The improved test requirements in the standards now ensure that ZnO surge arresters with porcelain housings which successfully pass the new tests have an acceptable performance when overloaded.

The maintenance team MT 4 (former WG4) of IEC TC 37 (surge arresters), responsible for updating the IEC 60099-1, 60099-4 and IEC 60099-6, has recently published an amendment to the gapless metal-oxide arresters standard (IEC60099-4 [3]). Because of lack of consensus, a mandatory short-circuit test procedure could not be formulated. Instead, an "informative annex" (annex O) is put forward. This being a non-satisfactory compromise, the MT is seeking for a revised procedure having international agreement.

An unresolved issue in the procedure for short-circuit testing is the need to reach an asymmetrical peak current value of 2.5 times the symmetrical RMS value (2.5 being the so-called asymmetrical current peak factor). This is difficult in case of both low source voltage of the short-circuit current circuit and high arcing voltage of the arrester fault arc due to the influence of arrester arcing voltage on the short-circuit current.

High arcing voltages are in particular associated with long arcs that occur with tall arresters i.e. arresters for high rated voltage, e.g. 120 kV. However, due to lack of gas space within arresters of type B1 and B2 even relatively short units of these arresters can give considerable arcing voltage. Then, the combined effects of these decrease the X/R ratio of the circuit below a level of approx. 15, necessary to reach the asymmetrical peak factor. As a rule of thumb, a housing length > 1.5 m and a voltage < 77% of the rated arrester voltage is critical in this respect.

A possible solution is to increase the RMS current, but, especially for the higher short-circuit current ratings of 63 and 80 kA, this is beyond the capability of most laboratories, let alone the unrealistic consequences it has for the arrester stress.

A questionnaire is sent by the MT out mid 2003 to make an inventory of current practices and capabilities in test laboratories world wide.

4b. Preconditioning prior to short-circuit tests

Test samples have to be conditioned before application of the short-circuit current. This conditioning can be either with a fuse wire, or electrically:

4b.1. Fuse wire

In this method, a fuse wire is applied between the arrester housing and the ZnO elements in case of a

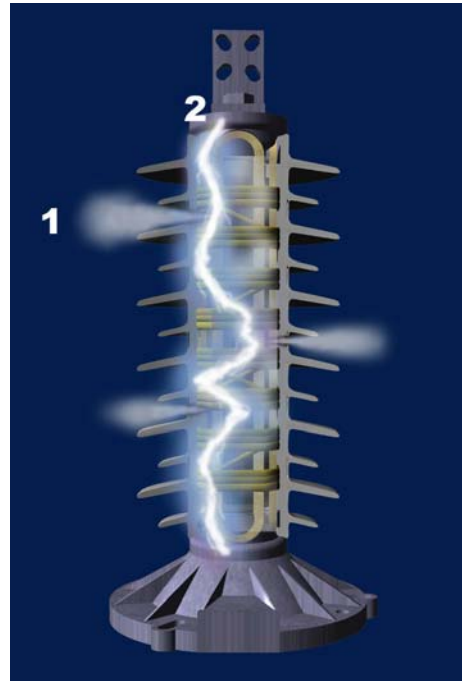


Fig. 2. Operating principle of moulded cage design.

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

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

arrester with pressure relief device or in a hole drilled near the centre of the active elements in case of an arrester without pressure relief device. As demonstrated in sect. 5b, the highest thermal stresses occur at the centre. The fuse wire shall melt within 30 el.deg. after test current initiation.

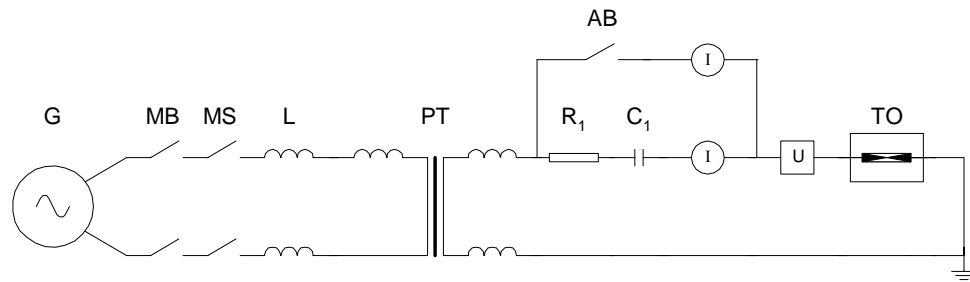


Fig.3: Test circuit for automatic transition from prefail into short-circuit. TO: tested arrester, AB: auxiliary circuit breaker; R₁, C₁: elements for adjustment of (pre-) failing current; PT: power transformer; MS: making switch; MB: master breaker; G: generator; L: reactor; I, U: current and voltage measurements

4b.2 Electric preconditioning

Electric conditioning does not need mechanical preparation of the sample, but a circuit, supplying a voltage approx. 15% higher than the rated arrester voltage must be available.

Short-circuit testing practice at KEMA of arresters consists of three distinct regimes or phases, characterised by the currents (mA, A, kA respectively) involved:

- milli Ampere (mA) phase. In this pre-failing phase, a small current 30 - 50 mA (current density 5 - 10 mA/cm²) is flowing through the arrester under the influence of a voltage of roughly twice the phase voltage. The related thermal stress leads to a voltage collapse to a value smaller than 10% of the originally applied voltage after 2 - 8 minutes. The circuit must then be able to provide sufficient energy to the pre-failed arrester by allowing current to increase to a level of 1 - 30 A.
- Ampere (A) phase. In this failing phase, the arrester is conditioned during a few seconds for the short-circuit test. Now, a low-current arc will establish, which will lead to a voltage across the arrester of several kV.
- kilo Ampere (kA) phase. In this phase, the full short-circuit current is supplied for at least 0.2 s.

The transition between these successive phases is of major importance. The transition from the mA to the A phase is continuous and realised without test circuit re-arrangement.

Generally, the test-circuit of fig. 3 is used at KEMA. In the mA and A phase, the source voltage is set to a value that electrically pre-fails the arrester; R₁, C₁ are set to limit the current to 30 A.

4c. Short-circuit test experience

The transition from the failed arrester into the short-circuit phase (from A to kA) needs a change of test-circuit parameters from high-voltage to high-current. Except for cases where sufficient direct power is available for performing both pre-fail and short-circuit current tests with a single circuit, some time (3 - 8 minutes) is needed to change the test-circuit parameters in order to enable short-circuit tests. At KEMA this implies removal of pre-failing current measurement, fixation of arrester to a pedestal, increase of the number of generators and lower transformer ratio. Also, R₁, C₁ are re-set in order to re-install 30 A at application of the lower voltage of the high-current circuit.

During this circuit re-arrangement a certain cooling down of the arrester will occur. Thus, at the moment of voltage re-application, the arrester needs a certain time to re-gain the conductivity it had in the A phase. To obtain an acceptable reproducibility, therefore, the pre-failing circuit has to be reapplied immediately before application of the short-circuit current. Without this reapplication and at a low source voltage and a tall arrester of type B1 or B2 the arrester may very well "wistand" the voltage and no short-circuit current will occur. After closing of the high-capacity circuit breaker AB the current will change from the 30 A current into the short-circuit current (set by L).

It is the experience that a certain time is needed to increase the arrester conductivity before full short-circuit current will develop. This is outlined in the oscillogram detail of fig. 4, where several ms are needed to increase the conductivity to the short-circuit value. Due to this delay, the asymmetric peak is difficult to reach (not the required 2.5 value in fig. 4) and becomes dependent on the applied

voltage¹. To shorten this delay time as much as possible, it is KEMA's policy to apply a voltage which is at least 7 times the arc voltage.

At very high-current (80 kA) there is no circuit breaker available, and voltage is applied on "cold" samples. In order to reach the 2.5 factor in such extreme cases, a three-phase circuit is used producing superasymmetry (dc component > 1) in one phase. In this way, peak currents up to 237 kA_{pk} have been realised through 36 kV class polymer arresters.

When tests at or near (not less than 77% of) the rated arrester voltage (U_r) can be performed, the IEC 60099-4 does not require to demonstrate that the 2.5 asymmetrical current peak factor is reached in the actual test. This is because, in this case, test conditions are the same as service conditions and any reduction in peak current value by arc voltage also will occur in service.

In the case that the combination of high voltage and high current is not available in one circuit in the laboratory, IEC suggests that tests at reduced voltage (<77% of U_c) can be done at the condition that the actual arrester test current shall reach the 2.5 asymmetrical peak factor².

In principle, the higher the current, the higher the Lorentz force that pushes away the arc from the arrester housing, thus limiting the thermal stress to it. This is the reason that IEC describes a test topology in which the current supply rods are located such that the resultant force on the arc pushes it against the housing (i.e. venting occurs in the supply current loop).

Due to the tendency of the arc to elongate in a direction away from the arrester body at higher current, lower currents are not per se lower stresses to the arrester housing.

Precautions are necessary to make sure that the arc roots do not leave the arrester terminals. This is normally done with an insulated supporting structure, combined with high-speed video supervision.

In this light, it can be commented that the emphasis on the importance of the asymmetrical peak current may be reconsidered:

1. there is no reason to consider the high peak current as the most onerous situation in terms of thermal stress (peak current is reached at a time the arc is already "outside" - see fig. 4);
2. in addition, the rate of energy input into the arc, still internalised just after short-circuit initiation is much faster with symmetrical current. This is causing a more severe pressure rise pattern than in the asymmetrical current case with its lower rate-of-rise;
3. it can be doubted whether the onset of short-circuit current in service is often at voltage zero.

It is KEMA's experience that initiation of short-circuit current 45 el.deg. after voltage zero has a more severe impact on isolating material and flanges because of:

1. Conduction is gained faster because switching in occurs already at a considerable voltage level (50% of peak voltage is immediately available instead of 0%);

¹ KEMA's limit to reach the 2.5 peak factor is:

80 kA @ 48 kV (2.5 m arrester) or 25 kA @ 72 kV (2.5 m) for tests with fuse-wire pre-conditioning (type A)
 80 kA @ 48 kV (0.6 m) or 25 kA @ 72 kV (1.5 m) for tests with electrical pre-conditioning (type B1/B2)
 The circuit's inherent (without test object) asymmetrical peak factor in these cases is 2.8

² As an example: the voltage drop across a high-current arc is approx. 25 V/cm. A 1.5 m tall arrester has a typical arc length of $1.5\pi/2 = 2.4$ m resulting in 6 kV arc voltage. The asymmetrical current peak with arrester can be reached then by applying an additional 6 kV on top of the test voltage of approx. $7 \cdot 6 = 42$ kV.

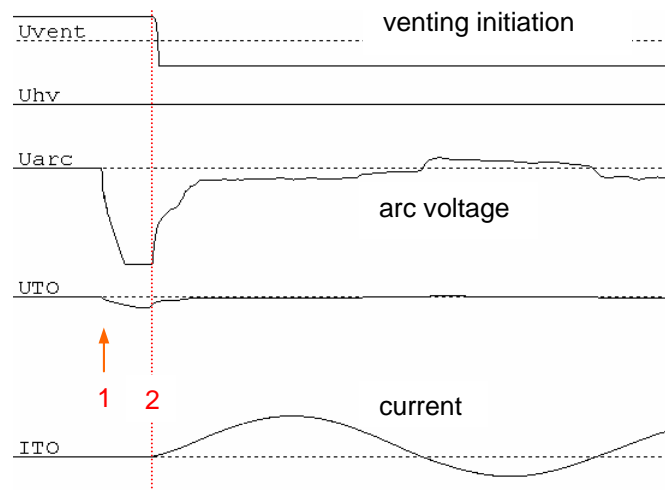


Fig 4. Application of voltage at voltage zero (arrow 1) leads to delayed high-current arcing (line 2) and venting

2. rate of rise of current within the first 2 ms is higher, causing more power input into the still internalized arc.

Dropping of the asymmetrical peak current requirement, apart from not representing the most onerous situation, as well as being less realistic, leads to a reduction of test expenses. Even the largest test laboratories cannot produce the asymmetrical peak for very high current with tall arresters. It is observed that the results in terms of the mechanical impact of the short-circuit stress depend on the way of pre-conditioning. For arresters of type B1 and B2 fuse-wire pre-conditioning shows a smaller damage than electrical pre-conditioning: the polymer remnants are "glued" onto the remaining structure after test, whereas the electric pre-conditioning leads to expulsion of polymer pieces, probably because higher temperature is reached in the latter method. There are no differences in the remnants of the active arrester parts.

5. FAILURE LOCATION

Whether a block overload results in a failure along the surface of the block stack or within the block volume greatly determines how the short-circuit performance will be and what precautions must be taken in the design of arresters of type B1 and B2. If, for these arrester types, a failure could always be guaranteed along the block surface, no block pieces would be ejected whatsoever, and the design could be made very simple. It is however much more complicated to ensure that no violent scattering of block pieces occurs if the initial failure takes place within the volume of the blocks.

Without special precautions, the edge of the ZnO blocks is normally a weak area. Failure under discharge operation may therefore have a higher probability to occur close to the block rim.

On the other hand, high-energy blocks with a uniform current distribution can, by overloading, result in failure anywhere on the surface during discharge operation.

A high-quality block (from an energy withstand point of view) and an "easy-to-handle" failure mode are thus somewhat in contradiction.

For failures occurring during TOV (temporary overvoltage) and overloading of high-quality homogeneous blocks, there is a higher probability that the initial failure occurs within the block volume and not at the edge of the blocks. The cooling of the block surface hereby also plays an important role, which will be discussed further below. For polymer housed arresters of the open cage and closed design, the cooling of the block surface is better than for the tubular design.

5a. Comparison with proposed test methods

The prefailing method, as proposed in the new IEC standard tests [3], usually results in an initial block failure within the ZnO block volume and not at the rim of the blocks. It has been argued that this type of failure mode is unlikely, or even impossible, to occur in practice. However, as discussed in section 3, many of the possible failure scenarios could lead to the same stress as used in the prefailing procedure as per IEC, even if the initial cause of failure is an impulse stress.

5b. Modelling of failure due to IEC method for prefailing

Partial failures of an arrester or flashover of one unit in a multi-unit design of arrester type B1 or B2 may result in a low current during a long time equivalent to a temporary overvoltage.

The blocks are thereby resultantly heated up. Due to the heat transfer from the blocks, the negative temperature coefficient below and around the "knee-point" as well as the extreme non-linearity, the centre of the blocks will reach a higher temperature than at the rim. The current density will also be higher which, in turn, increases the temperature, and so the cycle continues. In this case, the probability for a uniform block to fail close to the centre is higher than at the rim.

The case has been modelled and figure 5 shows the temperature distribution as a function of time within a 74 mm diameter ZnO block subjected to a voltage slightly above the reference voltage. The probability that the failure occurs closer to the centre than at the edge thus increases with time. For the case modelled, the block is surrounded by a silicone rubber insulator, which gives a good cooling of the rim, thus accentuating the differences within the block.

Finally, figure 6 shows a photo of a block failed due to this type of overloading. The short-circuit current was limited to approximately 30A.

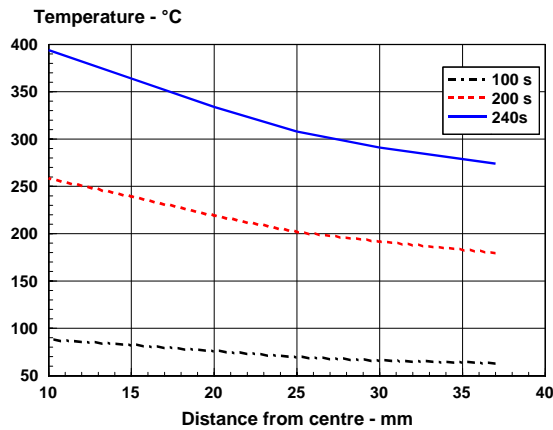


Fig. 5 Modelling of temperature distribution within a ZnO block after 100, 200 and 240 s with an applied voltage slightly above the ref. voltage



Fig. 6: Failure of a ZnO block due to TOV application. The block is punctured close to the centre. A silicone rubber insulator surrounds the ZnO block.

6. SOLUTION FOR SAFE SHORT-CIRCUIT PERFORMANCE: GENERAL CRITERIA

Different manufacturers have found different solutions suitable for their designs. However, in general, all successful designs of open and closed type polymer housed arresters must fulfill some basic requirements:

- The internal pressure must be able to be relieved quickly through the enclosure.
- Block (and other) pieces of hard material must not be expelled through the enclosure.
- The enclosure must be held together as much as possible.
- The arc should not be allowed to be established nor stay within the enclosure.
- The materials shall be self-extinguishing.
- The design must be able to handle failures occurring within the block volume close to the centre.
- The current arc must be commutated to the outside as quickly as possible.

7. CONCLUSIONS

With regards to short-circuit performance, the most severe case is a failure of the ZnO blocks close to the centre of the blocks. It is however unlikely that all failures occur in this way. Nevertheless, many realistic cases do exist which, with high probability, could lead to this type of failure. In addition, improved quality of the blocks also increases the "risk" that a failure occurs somewhere else than on the edge of the blocks.

From a standardization point of view, a pre-failing procedure resulting in higher risk for failure close to the centre of the blocks is therefore justified and recommendable. An arrester design must be able to handle this type of failure without a violent explosion.

From experience, the suggested requirement in the new IEC standard 60099-4 to apply a full asymmetrical current with a peak (80% dc component at the 1st peak) of 2.5 times the RMS short-circuit current is appearing not to be the most severe case.

Initiation of the current with a higher di/dt (>70% of its maximum and lasting for at least 3 ms) can be considered - in spite of a lower asymmetrical peak (<40% dc component at the 1st peak) - to cause a faster pressure rise prior to pressure relief by venting. Moreover, the arc, once externalized, causes a higher thermal impact on the housing because it "burns" closer to it.

Apart from this, the authors believe symmetrical currents have a higher probability to occur in service. Even the largest laboratories face difficulties producing the highest current with tall arresters. It is, however, necessary when testing polymer housed arresters of type B1 and B2 to use a well designed pre-failing procedure and test circuits to ensure reproducible test results.

References

- [1] INMR Vol. 10 No.6, November-December 2002.
- [2] INMR Vol. 11 No. 1, January-February 2003.
- [3] IEC Standard 60099-4, Edition 1.2. 2001-12, Annex O.