

# DESIGN AND TESTING OF POLYMER-HOUSED SURGE ARRESTERS

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## Abstract

Since some years, arresters with polymer-housings have been available on the market for distribution and medium voltage systems. In recent years, this type of arresters have been introduced also on higher voltage systems up to and including 550 kV. However, the international standardisation work is far behind this rapid development and many of existing designs with polymer-housings for high-voltage systems have only been tested according to the existing IEC standard, IEC 99-4 of 1991, which in general only covers arresters with porcelain housings.

The existing IEC standard lacks suitable test procedures to ensure an acceptable service performance and life time of a polymer-housed surge arrester. In particular, tests to verify the mechanical strength, short-circuit performance and life time of the arresters are missing.

In this report, different design alternatives are discussed and compared and relevant definitions and tests procedures regarding mechanical properties of polymer-housed arresters are presented. Necessary design criteria and tests to verify a sufficiently long life-time as well as operating duty tests to prove the arrester performance with respect to possible energy and current stresses are given. The advantages of silicon insulators under polluted conditions are discussed

Finally, this report presents some new areas of applications which open up due to the introduction of polymer-housed arrester designs. One such is protection of transmission lines against lightning/switching surges so as to increase the reliability and security of the transmission system.

## 1. INTRODUCTION

### 1.1 SHORT HISTORICAL BACKGROUND

Surge arresters constitute the primary protection for all other equipment in a network against overvoltages which may occur due to lightning, system faults or switching operations.

The most advanced gapped SiC arresters in the middle of 1970s could give a good protection against overvoltages but, the technique had reached its limits. It was very difficult, e.g., to design arresters with several parallel columns to cope with the very high energy requirements needed for HVDC transmissions. The statistical scatter of the sparkover voltage was also a limiting factor with respect to the accuracy of the protection levels.

Metal-oxide (ZnO) surge arresters were introduced in the mid of and late 1970s and proved to be a solution to the problems which not could be solved with the old technology. The protection level of a surge arrester was no longer a statistical parameter but could be accurately given. The protective function was no longer dependent on the installation or vicinity to other apparatus as compared to SiC arresters which sparkover voltage could be affected by the surrounding electrical fields. The ZnO arresters could be designed to meet virtually any energy requirements just by connecting ZnO varistors in parallel even though the technique to ensure a sufficiently good current sharing, and thus energy sharing, between the columns was sophisticated. The possibility to design protective equipment against very high energy stresses also opened up new application areas as, e.g., protection of series capacitors.

The ZnO technology was developed further during 1980s and in the beginning of 1990s towards higher voltage stresses of the material, higher specific energy absorption capabilities and better current withstand strengths.

New polymeric materials, superseding the traditional porcelain housings, started to be used 1986-1987 for distribution arresters. At the end of 1980s polymer-housed arresters were available up to 145 kV system voltages and today polymer-housed arresters have been accepted even up to 550 kV system voltages.

Almost all of the early polymeric designs included EPDM rubber as an insulator material but during the 1990s more and more manufacturers have changed to silicon rubber which is less affected by environmental conditions, e.g., UV radiation and pollution.

## 1.2 DIMENSIONING OF ZNO SURGE ARRESTERS

There are a variety of parameters influencing the dimensioning of an arrester but the demands as required by a user can be divided into two main categories:

- Protection against overvoltages
- High reliability and a long service life

In addition there are requirements such as that, in the event of an arrester overloading, the risk of personal injury and damage to adjacent equipment shall be low.

The above two main requirements are somewhat in contradiction to each other. Aiming to minimise the residual voltage normally leads to the reduction in the capability of the arrester to withstand power-frequency overvoltages. An improved protection level, therefore, may be achieved by slightly increasing the risk of overloading the arresters. The increase of the risk is, of course, dependent on how well the amplitude and time of the temporary overvoltage (TOV) can be predicted. The selection of an arrester, therefore, always is a compromise between protection levels and reliability.

A more detailed classification could be based on what stresses a surge arrester normally is subjected to and what continuous stresses it shall withstand, e.g.

- Continuous operating voltage
- Operation temperature
- Rain, pollution, sun radiation
- Wind and possible ice loading as well as forces in line connections

and additional, non-frequent, abnormal stresses, e.g..

- Temporary overvoltages, TOV
- Overvoltages due to transients which affect
  - thermal stability & ageing
  - energy & current withstand capability
  - external insulation withstand
- Large mechanical forces from, e.g., earthquakes
- Severe external pollution

and finally what the arrester can be subjected to only once:

- Internal short-circuit

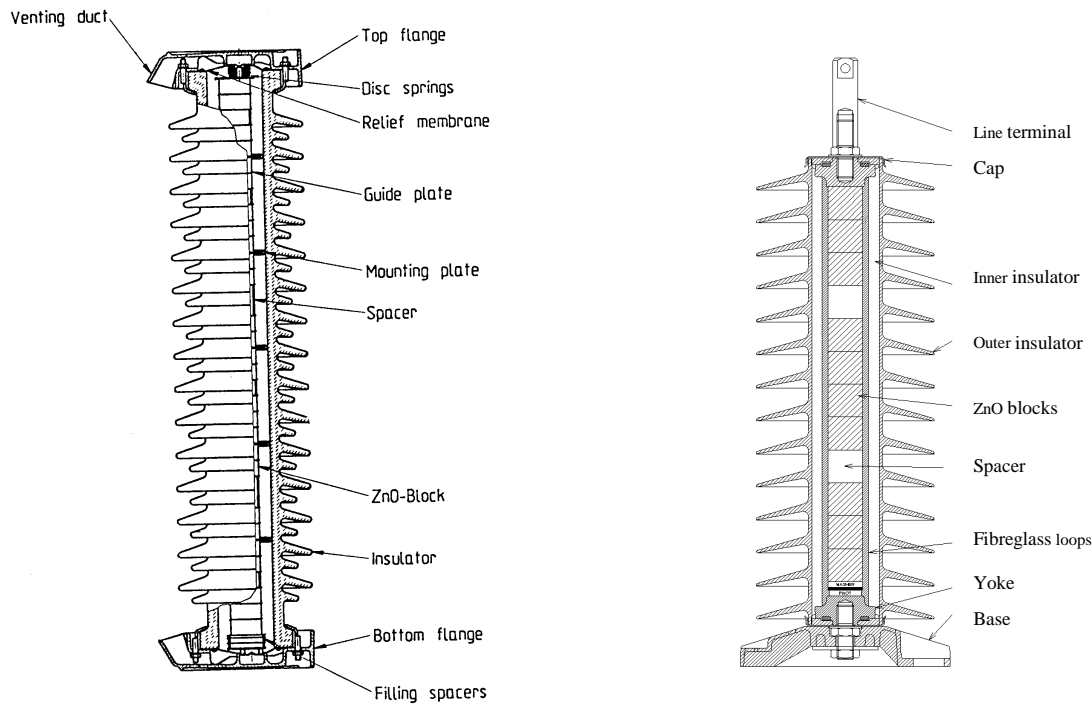
For transient overvoltages the primary task for an arrester, of course, is to protect but it must normally also be dimensioned to handle the current through it as well as the heat generated by the overvoltage. The risk of an external flashover must also be very low.

Detailed test requirements are given in International and National Standards where the surge arresters are classified with respect to various parameters such as energy capability, current withstand, short-circuit capability and residual voltage.

## 2. IMPORTANT COMPONENTS OF ZNO SURGE ARRESTERS

A ZnO surge arrester for high voltage applications constitutes mainly of the following components See **figure a**.

- ZnO varistors (blocks)
- Internal parts
- Pressure relief devices (normally not included for arresters with polymer-housings since these do not include any enclosed gas volume. The short-circuit capability of a polymer-housed arrester must therefore be solved as an integrated part of the entire design).
- Housing of porcelain or polymeric material with end fittings (flanges) of metal
- A grading ring arrangement where necessary



**Figure A:** Principal designs of porcelain- and polymer-housed ZnO surge arresters. The most important component in the arresters is of course the ZnO varistor itself giving the characteristics of the arrester. All other details are used to protect or keep the ZnO varistors together

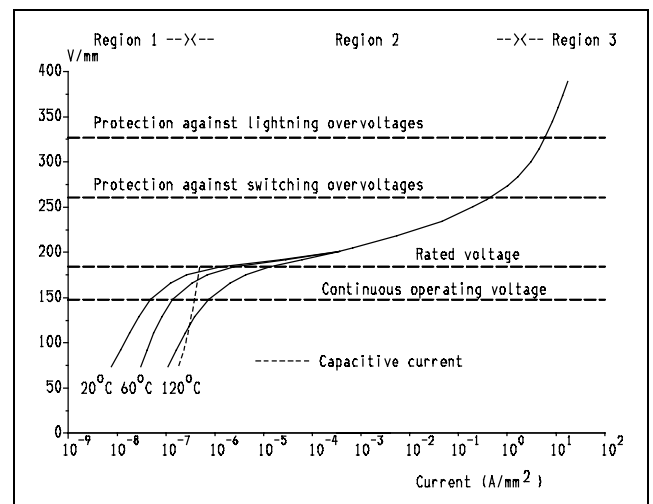
## 2.1 ZNO VARISTORS

The zinc oxide (ZnO) varistor is a densely sintered block, pressed to a cylindrical body. The block consists of 90% zinc oxide and 10% of other metal oxides (additives) of which bismuth oxide is the most important.

During the manufacturing process a powder is prepared which then is pressed to a cylindrical body under high pressure. The pressed bodies are then sintered in a kiln for several hours at a temperature of 1100 °C to 1 200 °C. During the sintering the oxide powder transforms to a dense ceramic body with varistor properties (see **figure b**) where the additives will form an inter-granular layer surrounding the zinc oxide grains.

These layers, or barriers, give the varistor its non-linear characteristics. Aluminium is applied on the end surfaces of the finished varistor to improve the current carrying capability and to secure a good contact between series- connected varistors. An insulating

layer is applied to the cylindrical surface thus giving protection against external flashover and against chemical influence.



**Figure B:** Current-voltage characteristic for a ZnO-varistor.

## 2.2 INTERNAL PARTS OF A SURGE ARRESTER AND DESIGN PRINCIPLES FOR HIGH SHORT-CIRCUIT CAPABILITY

For all the different types of housings, the ZnO blocks are manufactured in the same manner. The internal parts, however, differ considerably between a porcelain-housed arrester and a polymer-housed arrester. The only thing common between these two designs is that both include a stack of series-connected zinc oxide varistors together with components to keep the stack together but there the similarities end.

A porcelain-housed arrester contains normally a large amount of dry air or inert gas while a polymer-housed arrester normally does not have any enclosed gas volume. This means that the requirements concerning short-circuit capability and internal corona must be solved quite differently for the two designs.

There is a possibility that porcelain-housed arresters, containing an enclosed gas volume, might explode due to the internal pressure increase caused by a short-circuit, if the enclosed gas volume is not quickly vented. To satisfy this important condition, the arresters must be fitted with some type of pressure relief system.

In order to prevent internal corona during normal service conditions, the distance between the block column and insulator must be sufficiently large to ensure that the radial voltage difference between the blocks and insulator will not create any partial discharges.

Polymer-housed arresters differ depending on the type of design. Presently these arresters can be found in one of the following three groups:

- I. Open or cage design
- II. Closed design
- III. Tubular design with an annular gas-gap between the active parts and the external insulator

In the first group, the mechanical design may consist of loops of glass-fibre, a cage of glass-fibre weave or glass-fibre rods around the block column. The ZnO blocks are then utilised to give the design some of its mechanical strength. A body of silicon rubber or EPDM rubber is then moulded on to the internal parts. An outer insulator with sheds is then fitted or moulded on the inner body. This outer insulator can also be made in the same process as used for the inner body.

Such a design lacks an enclosed gas volume. At a possible internal short-circuit, material will be evaporated by the arc and cause a pressure increase. Since the open design deliberately has been made weak for internal overpressure, the rubber insulator will quickly tear, partly or along the whole length of the insulator. The air outside the insulator will be ionised and the internal arc will commutate to the outside. *figure m* illustrates this property vividly.

Surge arresters in group II have been mechanically designed not to include any direct openings enabling a pressure relief during an internal short-circuit. The design might include a glass-fibre weave wound directly on the block column or a separate tube in which the ZnO blocks are mounted. In order to obtain a good mechanical strength the 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 to a high value before cracking the tube which may lead to an explosive failure with parts thrown over a very large area. To prevent a violent shattering of the housing, a variety of solutions have been utilised, e.g., slots on the tubes.

When glass-fibre weave, wound on the blocks to give the necessary mechanical strength, is used, an alternative has been to arrange the windings in a special manner to obtain weaknesses that may crack. These weaknesses ensure pressure relief and commutation of the internal arc to the outside thus preventing an explosion.

The tubular design finally, is designed more or less in the same way as a standard porcelain arrester but where the porcelain has been substituted by an insulator of a glass-fibre reinforced epoxy tube with an outer insulator of silicon- or EPDM rubber.

The internal parts, in general, are almost identical to those used in an arrester with porcelain housing with an annular gas-gap between the block column and the insulator. The arrester must, obviously, be equipped with some type of pressure relief device similar to what is used on arresters with porcelain housing.

This design has its advantages and disadvantages compared to other polymeric designs. One advantage is that it is easier to obtain a high mechanical strength. Among the disadvantages are, e.g., a less efficient cooling of the ZnO blocks and 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. This latter problem can be solved by ensuring that the gap between the block column and insulator is very large but this leads to a costly and thermally even worse design.

Polymer-housed arresters lacking the annular gas-gap normally do not have any problem with corona during normal service conditions in dry and clean conditions. The design must be made corona-free during such conditions and this is normally verified in a routine test. However, during periods of wet external pollution on the insulator the radial stresses increase considerably. This necessitates that the insulator must be free from cavities to prevent internal corona in the material which might create problems in the long run. The thickness of the material must also be sufficient to prevent the possibility of puncturing of the insulator due to radial voltage stresses or material erosion due to external leakage currents on the outer surface of the insulator. The effects of external pollution are dealt with later on in the paper. See art. 3.2.5.

### 2.3 SURGE ARRESTER HOUSING

As mentioned before, the housings of the surge arresters traditionally have been made of porcelain but the trend today is towards use of polymeric insulators for arresters for both distribution systems as well as for medium voltage systems and recently even for HV and EHV system voltages.

There are mainly three reasons why polymeric materials have been seen as an attractive alternative to porcelain as an insulator material for surge arresters:

- Better behaviour in polluted areas
- Better short-circuit capability with increased safety for other equipment and personnel nearby.
- Low weight
- Non-brittle

It is quite possible to design an arrester fulfilling these criteria but it is wrong, however, to believe that all polymer-housed arresters automatically have all of these features just because the porcelain has been replaced by a rubber insulator. The design must be scrutinised carefully for each case.

Polymeric materials generally perform better in polluted environments compared to porcelain insulator. This is mainly due to the hydrophobic behaviour of the polymeric material, i.e., the ability to

prevent wetting of the insulator surface. However, it shall be noted that not all of the polymeric insulators are equally hydrophobic.

Two commonly used materials are silicon- and EPDM rubber together with a variety of additives to achieve desired material features, e.g., fire-retardant, stable against UV radiation etc. Polymeric materials can more easily be affected by ageing due to partial discharges and leakage currents on the surface, UV radiation, chemicals etc. compared to porcelain which is a non-organic material. Both silicon- and EPDM rubber show hydrophobic behaviour when new. The insulator made of EPDM rubber, however, will lose its hydrophobicity quickly and is thus often regarded as a hydrophilic insulator material.

Hydrophobicity results in reduced creepage currents during external pollution, minimising electrical discharges on the surface; thereby reducing the effects of ageing phenomena. The material can lose its hydrophobicity if the insulator has been subjected to high leakage currents during a long time due to severe pollution, e.g., salt in combination with moisture. The silicon rubber, though, will recover its hydrophobicity through diffusion of low molecular silicones to the surface restoring the original hydrophobic behaviour. The EPDM rubber lacks this possibility completely and hence the material is very likely to lose its hydrophobicity completely with time.

A safe short-circuit performance is not achieved only by using a polymeric insulator. The design must take into consideration what might happen at a possible failure of the ZnO blocks. This can be solved, depending on the type of design, in different ways as described in article 2.2.

Unfortunately, lack of relevant standardised test procedures for polymer-housed arresters has made it possible to uncritically use test methods only intended for porcelain designs [1,2]. This has led to the belief, incorrectly, that "all" polymer-housed arresters, irrespective of design, are capable of carrying enormous short-circuit currents.

The work within IEC to specify short-circuit test procedures suitable for polymer-housed arresters will be finalised soon [3]. The test procedures most likely to be adopted will, hopefully soon enough, clean the market from polymer-housed arresters not having a sufficient short-circuit capability.

The possible weight reduction compared to porcelain housed arresters can be considerable. As an example an arrester with porcelain insulator for a 550 kV system voltage has a mass of approximately 450 kg. A polymer-housed arrester for conventional up-right erection, with the same rated voltage, can be designed with a mass of approximately 275 kg. If suspended mounting is accepted, the weight can further be reduced to a total mass of only approximately 150 kg!

For long arresters for HV and EHV application, the desired increase in the mechanical strength of the housing is obtained by using additional stays of polymer material as can be seen in **figure c**.

Since the polymeric insulator, commonly silicon- or EPDM rubber, does not have the mechanical strength to keep the ZnO column together, other insulator materials must be used in the design. The most commonly used material is glass-fibre. There are several types of mechanical designs, e.g., cross-winding, tubes and loops.

Two main possibilities exist to combine the glass-fibre design and the insulator; firstly, the glass-fibre design can be moulded directly into the rubber insulator and secondly, the boundary between the glass-fibre and the rubber insulator is filled with grease or a gel, generally of silicon. It is of great importance that no air pockets are present in the design where partial discharges might occur leading to destruction of the insulator with time. Penetration of water and moisture must also be prevented which sets high requirements on the sealing of the insulator at the metallic flanges and adherence of the rubber to all internal parts in case the rubber is moulded directly on the inner design.

## 2.4 GRADING RINGS

Surge arresters for system voltages approximately 145 kV and above must normally be equipped with one or more metallic rings hanging down from the top of the arrester. The function of these rings is to ensure that the electrical field surrounding the arrester is as linear as possible. For very high system voltages, additional rings are used to prevent external corona from the upper metallic flange and from the line terminal.

## 3. DESIGN

### 3.1 DESIGNING FOR CONTINUOUS STRESSES

#### 3.1.1 CONTINUOUS OPERATING VOLTAGE

Denoted as  $U_c$  in accordance with the IEC standard,



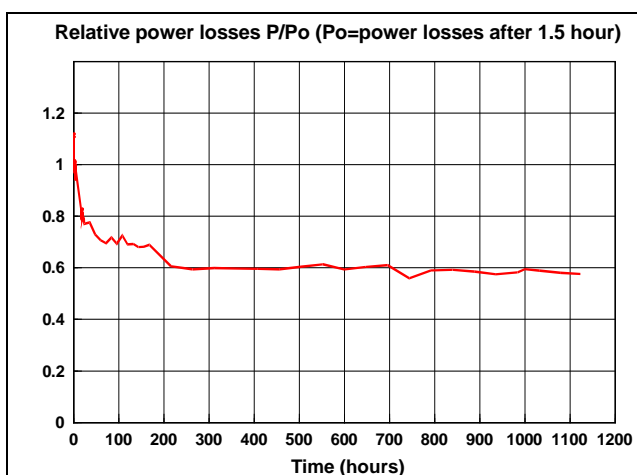
**Figure C:** Polymer-housed surge arrester for 550 kV system voltage. The surge arrester is designed to meet extreme earthquake requirements in the Los Angeles area (USA).

it is the voltage stress the arrester is designed to operate under during its entire lifetime. The arrester shall act as an insulator against this voltage. The entire voltage is across the ZnO varistors and these must be able to maintain their insulating properties during their entire lifetime.

The continuous operating voltage for AC surge arresters is mainly at power frequency, i.e., 50 Hz to 60 Hz with some percent of superimposed harmonics. For other applications, e.g. HVDC, the waveform of the voltage might be very complicated. The voltage might also be a pure DC voltage. It must be verified, therefore, for all applications that the ZnO varistors are able to withstand the actual voltage under their technical and commercial lifetime which normally is stated to be 20 to 30 years.

The basis for the dimensioning is the result from ageing procedures where possible ageing effects are accelerated by performing tests at an elevated temperature of 115 °C. For porcelain-housed arresters filled with air (sometimes nitrogen) it is not necessary to encapsulate the blocks during the test. For polymeric arresters, where the ZnO blocks are in direct contact with rubber, silicon grease or any other polymeric material, the ageing test must be made including these additional materials to verify that there are no negative effects, i.e., ageing of the blocks from the other materials.

The normal development of power losses for ZnO varistors is shown in **figure d**.



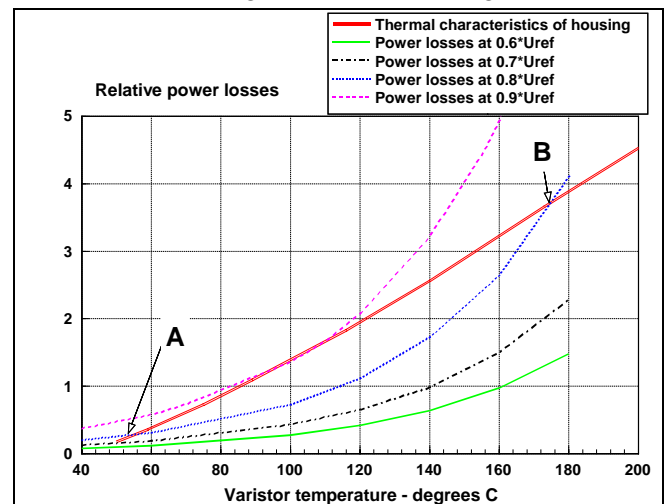
**Figure D:** Typical power losses during an accelerated ageing test at 115 °C and applied voltage ratio 0.97 times the reference voltage. Note that the test sample includes the polymer insulator moulded on to the ZnO blocks.

At voltage levels below the knee-point the ZnO block can be seen as a capacitor which is connected in parallel to a non-linear resistor. The resistance is both temperature- and frequency- dependent.

It is not sufficient just to check the behaviour of the ZnO varistor alone. The arrester must be seen as an integrated unit. The ability of the arrester housing to transfer heat must be considered and adjusted to the power losses of the ZnO varistors. This consideration must be made for different service conditions with respect to voltage, temperature and frequency to ensure that the continuous block temperature does not considerably exceed the ambient temperature.

If the power losses would increase with time, i.e., the ZnO blocks “age”, this must be accounted for in the dimensioning of the arrester.

**figure e** principally shows how the capability of the arrester housing to transfer heat and the temperature-dependent voltage-current characteristic in the leakage current region of a ZnO varistor results in a working-temperature at a certain ambient temperature and certain chosen voltage stress (A in the Figure).



**Figure E:** Thermal characteristics of a surge arrester housing and power losses for a ZnO varistor at different relative voltage stresses (ambient temperature +40 °C,  $U_{ref}$  = reference voltage)

An upper maximum temperature also exists (B in **figure e**) above which the design is no longer thermally stable for a given continuous operating voltage. If the temperature would increase above this value due to, e.g., transient or temporary overvoltages, the temperature will continue to increase until the arrester fails. The maximum designated  $U_c$  for an

arrester must thus be chosen with respect to possible power losses due to ageing, maximum ambient temperature, estimated energy absorption capability for transient overvoltages and temporary overvoltage (TOV) capability after the energy absorption.

When losses and possible ageing of the ZnO blocks are judged, a consideration of the complete arrester design must be made. The local voltage stress along a long arrester for high system voltages might deviate considerably from the average voltage stress. This, in turn, might lead to local heating of the upper part of the arrester and possible ageing of the ZnO blocks subjected to this high voltage.

It is essential, therefore, to distinguish between what the ZnO blocks can be subjected to without any encapsulation and how the design actually can be made taking into consideration that the ZnO blocks are encapsulated in a long arrester.

To ensure that the maximum stresses does not exceed given design criteria, the necessity of a suitable voltage grading must be considered. This is best accomplished with computer programs for electrical field calculations.

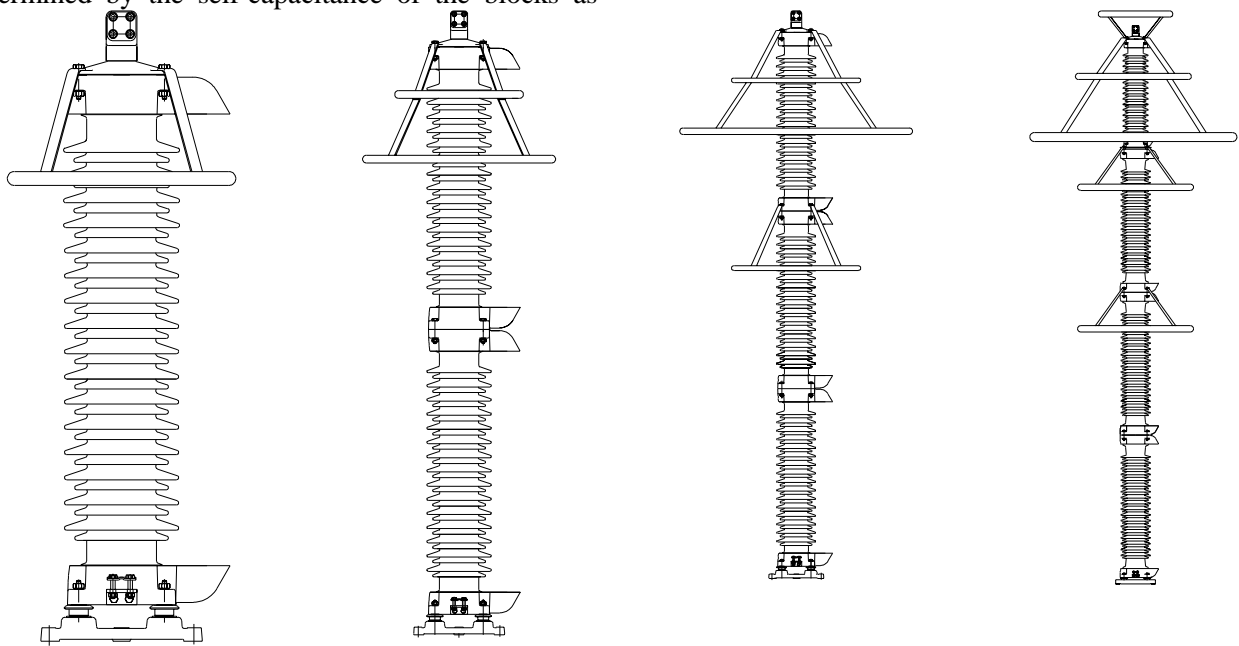
### 3.1.2 VOLTAGE GRADING

During normal operation conditions and operation voltages the ZnO blocks act like capacitors. The voltage across the ZnO blocks, therefore, will be determined by the self-capacitance of the blocks as

well as stray capacitance to the surroundings. For a long ZnO column, the self-capacitance of the ZnO blocks quickly becomes insufficient to ensure an even voltage distribution between the blocks. The surge arrester, therefore, must be equipped with some type of voltage grading. This can be achieved by additional grading capacitors and/or grading rings. Provision of grading rings is the most common way improving the voltage distribution.

The risk of local heating of the ZnO blocks (hot-spots), with consequent reduced energy absorption capability of the arrester, increases if the voltage distribution is not reasonably uniform along the whole arrester. Type tests in accordance with standards, to verify that the ZnO blocks are stable during sufficiently long time, are not valid either if the actual voltage stress on the arrester during actual service is allowed to exceed the applied voltage stress in the type tests.

An actual surge arrester installation constitutes a three-dimensional problem with three-phase voltages involved together with certain stipulated minimum distances between phases and to grounded (earthed) objects. All this must be considered when making a calculation. Not to consider the influence of adjacent phases, for example, will lead to an underestimation of the maximum uneven voltage distribution by up to 10 %.



System voltage 145 kV      System voltage 245 kV      System voltage 420 kV      System voltage 800 kV

**Figure F:** Examples on different grading ring arrangements for different system voltages. Note that the arresters are not shown to scale.

*figure f* shows the typical grading ring arrangement for arresters for different system voltages ( 145 to 800 kV).

Without using any components at all to improve the voltage grading, e.g., grading capacitors or suspended grading rings, the voltage across individual ZnO blocks at the line-end of a long arrester will be above the knee-point of the current-voltage characteristics, i.e., where the blocks start to conduct large currents. This current is determined by the applied voltage and the total stray-capacitance of the arrester to earth and can, for high voltage arresters, be considerable.

Big metallic electrodes, e.g., metallic flanges or rings to reduce corona without any suspension from its electrical contact point to the arrester, increases the stray-capacitance to earth amplifying the uneven voltage distribution.

### **3.1.3 MECHANICAL DESIGN OF POLYMER-HOUSED ARRESTERS**

Continuous stresses on polymeric materials must be selected with respect to the material behaviour of the polymer. Many of these characteristics are strongly dependent on temperature and load time. Polymeric materials becomes softer at higher temperatures with a higher degree of creeping (cold flowing), at cold temperatures the material becomes brittle.

It therefore is of great importance that the arrester design is tested with different temperature and load

combinations to verify that all possible sealings operate adequately in the entire temperature interval.

Composite materials, e.g., glass-fibre joined in a matrix with epoxy or other polymeric materials, exhibit behaviour changes at high loading. The rate of this material degradation is determined by temperature, applied force, velocity of the applied force, humidity and the time during which the load is applied. It is not sufficient, therefore, just to dimension the arrester with respect to its breaking force but consideration must also be taken to how the arrester withstands cyclical stresses.

Up to a certain mechanical load, the fibres of the composite material will not break (degrade). This is the maximum load, defined in terms of the maximum usable bending moment (MUBM), that can be applied continuously in service. This value has very little spread between different housings of the same type

unlike that for porcelain for which large safety margins are recommended due to the spread in the breaking moment.

The MUBM limit is best verified by measuring the acoustic emission to determine what forces might be applied on the arresters without long-term degradation of the composite materials. The MUBM value should be compared with the “static load” limit for porcelains which is 40% of the minimum breaking moment (as defined in DIN 48113).

At a value slightly above the MUBM, some fibres may start to break. When enough fibres break, there is a small change in the mechanical properties when stressed above MUBM again. A permanent deflection results when sufficient number of fibres are broken. Thus small overloads beyond MUBM have no significant impact on the service performance.

The new IEC standard, [3] will include a test where the arrester is subjected to both thermal as well as mechanical cycling. After the cycling, the arrester is placed in boiling water for 42 hours where moisture is given time and possibility to penetrate the arrester. Electrical measurements are made both before and after the test sequences to verify that the specimen has not absorbed any moisture. If the electrical characteristic of the arrester has changed during the tests, the most likely conclusion is that moisture has penetrated into the design which might imply that the arrester no longer fulfils the original requirements.

Since the polymeric arresters are elastic, temporary loads, like short-circuit forces and earthquake forces, can be looked upon differently compared to rigid bodies like porcelain insulators. The reason for this is that the forces do not have time to act fully due to the elasticity of the material and mass inertia, i.e., the forces are spread in time leading to that the arrester will not encounter any high instantaneous values. These advantages, combined with a design with small mass participation, have been fully utilised for the 550 kV arrester shown in **figure c**. This arrester withstands a ground horizontal acceleration of 0.5 g corresponding to the highest seismic demands as per IEEE/ANSI standards without any problems at all.

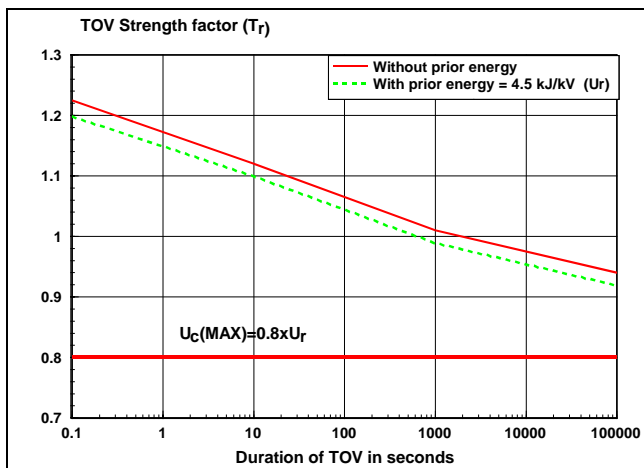
### **3.1.4 INTERNAL PARTS**

A low corona (partial discharge, PD) level is desirable for all apparatus designs intended for high voltage applications during normal service conditions. Porcelain arresters, though, will have large voltage

differences between the outside and inside of the arrester during external pollution and wetting of the porcelain surface. To fully avoid corona under such conditions will not give technically and economically defensible designs. Instead the internal parts including the ZnO blocks must be able to withstand these conditions.

For polymeric arresters, lacking such annular space in the design, the voltage difference is entirely across the rubber insulator. In order to avoid puncturing of the insulator the rubber must be sufficiently thick. It is also very important that the insulator does not have any air pockets which might give internal corona which, with time, may destroy the insulator.

The allowable voltage stress across the material is proportional to the length of the insulator. A longer insulator, therefore, requires that the thickness of the material is proportionally increased with respect to the increase in length.



**Figure G:** TOV capability for polymer-housed line discharge class 3 arrester as per IEC

Another solution is to reduce the height of the individual units in a multi-unit arrester, since the maximum voltage across each unit is limited by the non-linear current-voltage characteristic of the ZnO blocks. In order to verify the withstand against these type of stresses, IEC has proposed a long-time test under continuous operating voltage with continuously applied saltfog [3]. The test must be made on the longest arrester housing for at least 1 000 hours.

### 3.2 DESIGNING FOR NON-CONTINUOUS STRESSES

#### 3.2.1 TEMPORARY OVERVOLTAGES

TOV may occur in networks at, e.g., earth-faults. This is a voltage which, by definition, is above  $U_c$  and

normally will last from some few periods up to some seconds. In certain isolated systems, the duration of an earth-fault may last some days. The TOVs are normally preceded by a switching surge.

A ZnO arrester is considered to have withstood a TOV if:

- the ZnO-blocks are not destroyed due to energy under the TOV i.e. cracking, puncturing or flashover of the blocks does not occur.
- the surge arrester is thermally stable against  $U_c$  after cessation of the TOV

Since the leakage current through the arrester is temperature-dependent, see also **figure b**, fulfilling b) above is also dependent on the final block temperature. If, for example, due to a switching surge, the arrester already has a high starting temperature before being subjected to a TOV, it will naturally have a lower overvoltage capability.

This is exemplified in **figure g** showing the ability of a ZnO arrester to withstand overvoltages with or without a preceding energy absorption. The lower curve is valid for an arrester which has been subjected to maximum allowable energy, e.g., from a switching surge prior to the TOV. The upper curve is valid for an arrester without prior energy duty.

With ZnO arresters the TOV amplitudes are normally at, or immediately above, the knee-point of the current-voltage characteristic. If the arrester is designed fulfilling the IEC standard, it shall be able to withstand a TOV equal to the rated voltage of the arrester for at least 10 seconds after being subjected to an energy injection corresponding to two line discharges as per relevant line discharge class of the arrester.

The TOV is generally regarded as a stiff voltage source, i.e., the surge arrester cannot influence the voltage amplitude. For a dimensioning to fulfil a certain TOV level, the varistor characteristic must be chosen so the current through the arrester, and consequently the energy dissipation, will not result in a temperature above the thermal instability-point.

The TOV capability given for a certain surge arrester should always be assumed with a stiff voltage source. However, if this is not the case, the TOV capability of the arrester, in general, is significantly higher.

An important parameter concerning the dimensioning for TOVs is to accurately control the knee-point voltage since the non-linearity of the characteristic is in its extreme in the TOV range. This is best made by defining a reference voltage close to the knee-point on the voltage-current characteristics and then, in routine tests, checking that every arrester has a reference voltage above a guaranteed minimum voltage.

A distinct advantage with polymer-housed arresters is the superior heat transfer which leads to shorter cooling times and possible higher  $U_c$  or acceptance of a higher ambient temperature (above IEC stipulations) as is often the case in tropical desert climates. This is illustrated in **figure h**. The voltage after the energy injection was purposely increased to induce a thermal runaway in the porcelain-housed sample. At the same conditions, the polymer-housed sample was thermally stable.

A manufacturer is free to assign any data for the arresters. A given arrester with ZnO blocks capable to absorb high energies, therefore, could be assigned a very high line discharge class with low TOV capability or, on the contrary, a low line discharge class with high TOV capability.

### 3.2.2 TRANSIENT OVERVOLTAGES - ENERGY CAPABILITY - CURRENT WITHSTAND STRENGTHS

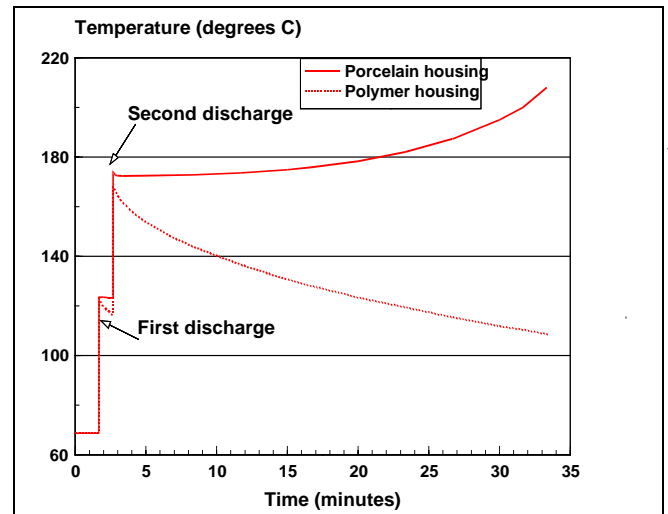
A surge arrester may in service be subjected to different energy impulses originating from, e.g., lightning, faults in the net-work and switching of lines and/or capacitor banks.

The arresters must be designed in such a way that the ZnO blocks will withstand the energy or current without failing. Additionally the arrester must be able to withstand the energy thermally, i.e., it must be able to cool against  $U_c$  after an energy absorption.

High voltage arresters are normally designed for a specific line discharge class. **figure i** shows relative energies in kJ/kV rated voltage for the different line discharge classes. The intention with the classification is naturally that a higher class should represent a higher energy capability for a given arrester. This is true, however, only if the ratio between the switching impulse residual voltage to the rated voltage of the arrester is approximately a factor of two. If the residual voltage is much higher, the line discharge class will become a useless quality measure.

The rated energy is often given in catalogues in kJ/kV rated voltage. Since the ZnO blocks normally are able

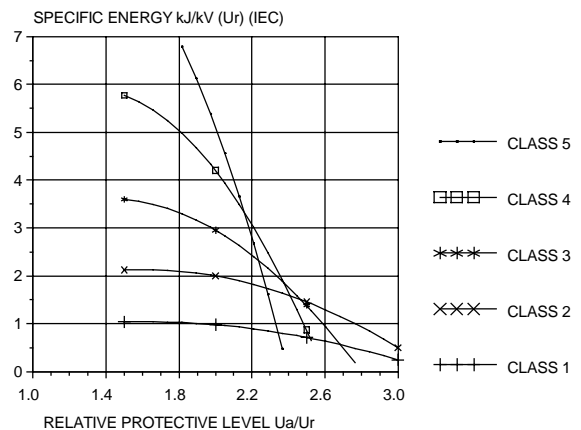
to withstand sufficiently higher energies for longer times, seconds, compared to shorter times, e.g., milli seconds, the expression itself is meaningless if, at the



**Figure H:** Oscillogram from an operating duty test showing the superior cooling properties of polymer housing.

same time, the shortest time for which the arrester can be subjected to the given energy is not stated.

A surge arrester may contain a large number of ZnO blocks and if just one of these blocks fails during an overvoltage the probability for a failure of the complete arrester is significant. The failure rate for a single ZnO varistor, therefore, must be extremely small to obtain a high reliability of the complete arrester. One way to guarantee a low failure rate is to routine-test all manufactured varistors with an energy considerably exceeding the corresponding varistor energy at the given rated energy for the arrester.



**Figure I:** Relative energy stresses for different line discharge classes according to IEC

As mentioned before, a high voltage arrester is normally designed in compliance with a chosen line discharge class as per IEC with respect to energy. For non-standard stresses, e.g., capacitor discharges or high energies due to lightning, the design is normally made with a lower energy stress per varistor.

The ZnO blocks, apart from withstanding the energy from current impulses, also must have a sufficiently high dielectric withstand ensuring that the voltage across the block will not result in a puncture or a flashover across the block. To ensure a sufficient insulation withstand margin for normal stresses, the ZnO blocks, including all internal parts in a high voltage arrester, are dimensioned to withstand current impulses with an amplitude of at least 100 kA having a wave form of 4/10  $\mu$ s. Requirements with very high energy absorption capability cannot be solved by using ZnO blocks with ever larger volumes but must be solved by connecting ZnO varistor columns and arresters in parallel.

To ensure that such designs will operate correctly during service, a very careful procedure is required to ensure a good current sharing between the block columns connected in parallel. Furthermore, possible changes of the block characteristic due to the normal applied service voltage as well as energy- and voltage stresses must be extremely small.

From protection perspective, it is acceptable that the residual voltage decreases due to repeated current impulses. When parallel connection of ZnO blocks is utilised, the acceptable deviations, however, are much lower than what the IEC standard permits (+/- 5%).

### 3.2.3 TRANSIENT OVERVOLTAGES - EXTERNAL INSULATION

In contradiction to other apparatus, the insulation level for surge arresters does not need to fulfil a standardised insulation class since the arrester effectively will protect its own insulation against overvoltages. Distance effects need not be considered. Instead, the Standards stipulate a specific safety margin between the residual voltage of the arrester and the voltage withstand level of its external insulation. The complete arrester, including possible grading rings, therefore must be designed to give a reasonable safety margin against external flashover during an overvoltage.

IEC requires the following minimum external insulation levels for an arrester housing:

#### Arresters with a rated voltage < 200 kV

- a) For a standard lightning impulse, 1.3 times the residual voltage at the nominal current with a wave shape 8/20 $\mu$ s
- b) For power frequency, 50/60 Hz (peak value), 1.06 times the residual voltage at the classifying current with a wave shape 30/60 $\mu$ s

#### Arresters with a rated voltage $\geq$ 200 kV

- a) For a standard lightning impulse, 1.3 times the residual voltage at the nominal current with a wave shape 8/20 $\mu$ s
- b) For a standard switching impulse, 1.25 times the residual voltage at the classifying current with a wave shape 30/60 $\mu$ s

The tests with switching impulses and power frequency are made as wet tests if the arresters are to be installed outdoors. With the specified margins to the protection characteristic of the arrester, an acceptable low risk for external insulation failure is obtained up to an installation altitude of 1 000 m above sea level as required by IEC.

All distances between the different parts of a surge arrester, e.g., grading rings to flanges or between flanges of the individual units or distances to earthed (grounded) equipment and to adjacent phases, must be verified with respect to voltage stress and voltage withstand. The complete arrester should preferably be tested to verify the withstand values even though the present IEC standard does not so stipulate [2].

The ZnO blocks cannot be included during these tests since test equipment capable of generating the required high currents does not exist. In order to emulate actual service conditions as much as possible, the ZnO blocks should, for a multi-unit arrester, be replaced by grading capacitors. If the ZnO blocks are removed without any replacement for the voltage grading, the test result may not be conservative.

### 3.2.4 TRANSIENT OVERVOLTAGES - PROTECTIVE FUNCTION

The arrester shall, for an expected maximum current, limit an overvoltage to a level well below the insulation withstand level of the protected equipment.

The protective characteristic for a ZnO varistor is slightly dependent on the steepness of the expected current. **figure j** shows the characteristic for a specific arrester for the three different current shapes given in

the arrester Standards. As can be noted from the diagram, the protection level for currents having a front time of 1  $\mu$ s are approximately 10% higher compared to currents with a wave form 8/20  $\mu$ s or longer. However, even more important than this marginal increase, for currents in the  $\mu$ s region, is the effect of positioning the arrester in relation to the protected equipment and the length of the connections. There is also an effect due to the arrester height.

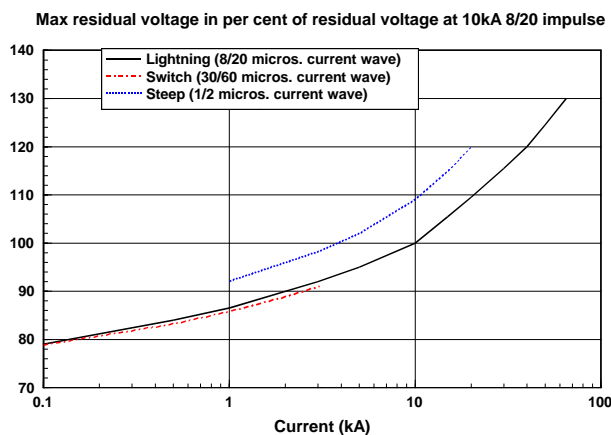
In order to obtain an efficient protection against fast transients, e.g., backflashover close to a substation, large margins, therefore, are required between the protection level of the surge arrester and the protected equipment's insulation level.

ZnO blocks with larger diameter has normally a better protection level with maintained overvoltage capability. A better protection level gives also automatically a better energy capability.

### 3.2.5 EXTERNAL POLLUTION

External pollution may influence a surge arrester as follows:

- Possibility of internal corona
- External flashover
- Heating of the ZnO blocks
- Tracking and erosion of insulator (polymer-housed arresters)



**Figure J:** Protective characteristic for a polymer-housed surge arrester with nominal discharge current 20 kA. The protection level is given in % of the 10 kA level which is checked in a routine test

The problems for arresters with porcelain housings installed in extremely polluted areas have been solved by greasing the insulator thus improving the pollution performance. The aim of the greasing is to reduce the leakage currents on the insulator surface. Hydrophobic

materials, like silicon rubber, give a similar effect. This is one strong motive why silicon rubber has been seen as an attractive insulator material.

A common conception is that polymer-housed arresters have a better pollution performance compared to porcelain. However, a more correct statement should be that hydrophobic materials have better performance in polluted areas due to reduced leakage currents. EPDM rubber, that loses its hydrophobic properties quickly, must be designed in the same manner as porcelain from pollution point of view.

It is very difficult to avoid internal corona, as discussed previously, during severe external pollution on arresters containing an annular gap between the ZnO blocks and the insulator as in the case of arrangements similar to porcelain-housed arresters. The design of such arresters, therefore, must be able to withstand corona during such occasions.

Some rules-of-thumb for designs like these are:

- "No" corona in dry conditions
- Minimise the use of organic materials. When organic materials are used they must have been thoroughly tested and subjected to a realistic corona test
- Prevent the possibility of electrical discharges directly on to the ZnO blocks

Concerning polymer-housed arresters, large radial voltage stresses may occur between the blocks and the outside of the insulator during severe external pollution. It is very important, therefore, that the rubber insulator is thick enough to avoid a puncture of the insulator. If such a design includes large air pockets or cavities, corona might occur that eventually leads to an arrester failure. As mentioned before, a supplement to the IEC standard will most likely be issued with requirements on a 1 000 hours test with continuous saltfog to verify the long-term stability of the insulation [3].

To avoid external flashover the creepage distance of the arrester, i.e. the shed-form and the length, is designed in compliance with the same criteria valid for other insulation at the actual site.

Possible thermal stresses are determined by the leakage currents that might be present on the outer surface of the insulator. For porcelain arresters it has been shown that the integral of the leakage current, i.e. the charge, can be regarded as independent of the

creepage distance but it is approximately linearly dependent on the diameter of the porcelain. An insulator with a larger diameter thus may give rise to higher thermal stress during conditions with external pollution, provided the service conditions otherwise are the same.

For applications requiring arresters with parallel housings and several units connected in series, the general rule is that the units should not be connected in parallel except at the top and bottom. This is because, in such an event, the ZnO blocks in one unit could conduct the external leakage current from all of the parallel connected arresters. Since the ZnO blocks have a negative temperature coefficient in the leakage-current region, a heating of one unit will lead to a reduction of the voltage characteristic with subsequent increase of the current. An increased current through the unit leads to higher power losses with increased temperature etc. Not even a careful current-sharing test of the arrester units will be of any help below the knee-point of current-voltage characteristic. However, above the knee-point the characteristic has a slightly positive temperature coefficient.

Improvement in a ZnO arrester's external pollution withstand, during otherwise similar conditions, is obtained by:

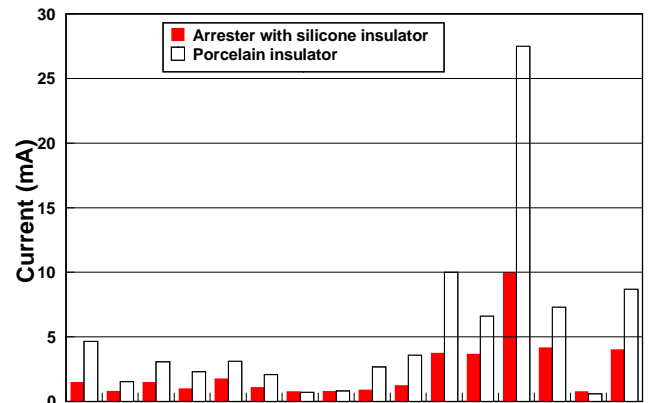
- Higher rated voltage, i.e., a higher TOV capability
- Higher energy capability, i.e., normally a larger block volume
- Improved heat conduction - higher thermal stability point
- Lower power losses at continuous operating voltage
- Lower leakage currents on the insulator surface

Lower leakage currents on the insulator surface is achieved by a hydrophobic surface. **figure k** shows leakage currents as measured on a porcelain insulator and a polymeric arrester for 145 kV systems having a silicon rubber insulator. The values are taken from an on-going test at NGC's test station at Dungeness at the English Channel. As can be noted, the amplitudes of the leakage currents are roughly half to a third of the corresponding leakage currents on the surface of the porcelain insulator during this specific measuring interval.

All the tests carried out and the operating experience gained so far indicate that the external creepage distance for polymer-housed arresters could be shorter

than that for equivalent porcelain-housed arresters by one class (as defined in IEC 815). This would be of great advantage for use in desert climates where the need for the necessary high creepage leads, at present, to expensive and difficult designs in porcelain housings.

**Daily maximum currents in a 16 days period at Dungeness test station**



**Figure K:** The leakage currents for 145 kV polymer-housed surge arrester and porcelain insulator at Dungeness test station. The leakage current for the arrester includes an internal leakage current of around 1 mA. The creepage distance for the polymeric arrester is 5 148 mm and 4 580 mm for the porcelain insulator.

### 3.3 DIMENSIONING FOR HIGH SHORT-CIRCUIT PERFORMANCE

As mentioned previously, the primary duty of a surge arrester, viz. to protect other equipment under all circumstances, gives a slightly higher risk of failure compared to other high voltage apparatus, which is accepted generally.

Since the risk of failure is not negligible, specific requirements are set on arresters to ensure that possible failures will not give consequential damages on other equipment, or, lead to unacceptable risk for people. Tests, where the internal parts are deliberately short-circuited, are also required, therefore, in the Standards. From design point-of-view, the aim is to ensure that the arrester housing is not scattered after a possible overloading.

In the existing Standard dealing with short-circuit tests, IEC 99-1 (being the old surge arrester Standard for gapped SiC arresters), it is taken for granted that an

arrester fulfilling a certain current class, with respect to short-circuit performance, automatically also fulfils lower current requirements. Recently it has been found that this is not always the case. A design might have "grey zones" if only tested with the highest possible current amplitude. A test made on the longest insulator used for a specific arrester design, is also considered to cover shorter insulators.

Discussions are going on within IEC on how the internal short-circuit shall be made before applying of the short-circuit current. A thin fuse-wire, arbitrary located, might not represent an actual fault-event, especially if the design is non-symmetrical with respect to arrangement of the pressure relief devices. It has been discussed, therefore, to place the wire in a location where it would represent the worst case for different design types and this requirement will be included in the Standard.

How to perform short-circuit tests on polymeric arresters, with no internal channels for a pressure relief, is another question discussed within IEC. As mentioned previously, it is not possible to uncritically apply test methods intended for porcelain arresters on polymeric designs. To perform tests by arbitrarily short-circuiting a polymeric arrester with a fuse-wire located alongside the block column, inside the external insulator, could result in that unsafe arresters are believed to be completely safe.

A suggested revision of the IEC Standard will most probably lead to tests on arresters at approximately 25%, 50% and 100% of the classifying short-circuit current. How the tests are performed are so far only defined in IEC 99-1 but a working group within IEC (IEC TC37 WG4) is working to revise the test procedure. The present tests shall be made with a high current, 16 kA to 80 kA, as well as with a low current, 400 A to 800 A.

The test duration is 0.2 seconds during the high-current test which reflects the time it takes a circuit breaker to disconnect a fault. To avoid an explosion of the arrester housing the internal arc must, in most cases, be commutated to the outside of the arrester within the first half-period of the short-circuit current. Since this time is critical, a certain current amplitude is defined for the first major loop of current, being 2.6 times the prospective symmetrical fault current. For the low current test, 600 A to 800 A, the current is maintained until opening of the pressure relief device occurs, which shall take place within 1 second.



*Figure L: A polymer-housed arrester prior to a short-circuit test.*



*Figure M: The same arrester after a short-circuit test at 50 kA sym*

The most likely test procedure, according to IEC, will give two possibilities, two test methods, to obtain an internal short-circuit. The first method is to provoke a short-circuit of the ZnO blocks by applying a sufficiently high voltage on the arrester leading to an electrical failure in two to eight minutes where after the arrester shall be subjected to the short-circuit test (high current) within five minutes. The second alternative is to short-circuit the arrester with a thin fuse-wire through a pre-drilled hole between the centre and the periphery of the blocks. This latter method is considered to be the worst-case model.

The pictures in **Error! Reference source not found.** and **Error! Reference source not found.** show the results of a short-circuit test at 50 kA, performed in accordance with the proposed IEC standards.

#### **4. VERIFICATION OF SURGE ARRESTER DESIGN**

Set requirements on a surge arrester and the design of the same are considered to be satisfactory verified by having the arrester subjected to the following tests:

- Residual voltage measurement at different current amplitudes and wave-shapes
- Current impulse withstand tests
- Operating duty test
- Accelerated ageing test
- Artificial pollution test
- External insulation test
- Short-circuit test
- Mechanical test

The above tests are considered to be type tests (design tests) but some of these may also be performed during the manufacturing process and/or assembly as a part of a manufacturer's quality assurance. The protective characteristic is verified during the various residual voltage tests.

The reliability is checked through a number of electrical and mechanical tests. An important part of the electrical tests is the operating duty test in which an arrester, or a pre-scaled model of the arrester, is subjected to a combination of stresses representing anticipated service stresses that an arrester might be subjected to during its lifetime.

The lifetime is finally verified by subjecting the ZnO blocks to an accelerated ageing test procedure.

Within IEC, TC37 is responsible for the standardisation of surge arresters. The working group responsible for the new Standard for gapless metal-oxide arresters, IEC 99-4, is named IEC TC37 WG4. This working group will continue its work also after publishing of the new standard. The group shall propose, among others, a test method for artificial pollution on ZnO arresters, something that still is lacking in the new Standard.

In the forthcoming Standard on polymer-housed arresters, the test procedures will differ considerably from previous tests on porcelain designs. A tightness check will e.g., be required to verify that polymeric arresters will not absorb moisture [3]. According to the suggested test procedure, the arrester shall be subjected to both mechanical and electrical tests before immersed in boiling salt water. After the boiling, the electrical tests will be repeated to verify that the characteristic has not changed, something which could indicate penetration of water.

#### **5. SPECIAL APPLICATIONS OF POLYMERIC ARRESTERS - LIGHTNING & SWITCHING PROTECTION OF TRANSMISSION LINES**

##### **5.1 LIGHTNING PROTECTION OF TRANSMISSION LINES**

Transmission lines in the lower system voltage range, 70 kV - 245 kV, are often sensitive to lightning overvoltages due to that:

- the insulation withstand is relatively low
- the transmission line often lacks shielding wires
- the footing impedance of the towers is high
- the transmission line lacks a continuous counterpoise (earth wire)

Despite this, meshed networks with rapid re-connection of faulty lines give satisfactory operation safety. Short-time disturbances (around 0.5 seconds) must be ignored, however, in radial nets as well as the voltage drop during the fault time (around 0.1 second) occurring also in the meshed nets.

There are, however, some types of loads where even the shortest disturbance is of greatest importance; e.g. process industries as steel mills, paper mills and refineries. For these loads, even a very short disruption or voltage drop could lead to unacceptable

interruption of the on-going processes. The cost for such an interruption is both the value of lost production and the costs to re-start the production. The accumulated sum for these costs can be very high. In a de-regulated energy market such costs will be more visible to the network operator than before, since the buyer could set new, higher demands on delivery security.

## 5.2 SURGE ARRESTERS FOR TRANSMISSION LINE PROTECTION AND THEIR DESIGN

What could then be done to increase the delivery security with respect to faults caused by lightning? The traditional methods to reduce the number of faults caused by lightning have been:

- installation of shield wires
- improvement of the earthing impedance of the towers
- increasing the insulation level

Unfortunately, implementing the above gives only marginal improvements of the delivery security, especially if the earthing conditions are difficult due to a high earth resistivity.

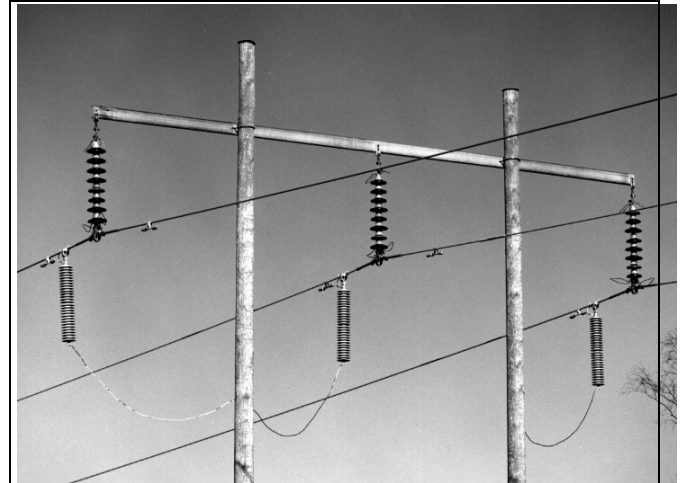
A new possibility to reduce the number of line faults caused by lightning is to install metal-oxide surge arresters with polymeric insulators in parallel with the line insulators. These transmission line arresters (TLA) normally consist of standard polymer-housed arresters together with a disconnecting device and fastening equipment for installation on the line itself or on the tower.

Transmission line arresters give complete protection against lightning flashovers for the actual line insulator. Insulators in adjacent phases and in other towers, however, are not protected; why TLA should be installed on all phases on the towers that are intended to be protected.

In reality, TLA are seldom installed throughout an entire line length but only in areas where lightning gives most problems due to exposed position, bad earthing conditions etc. Modern localisation systems for lightning-storms in combination with traditional fault statistics are excellent tools to identify towers where TLA should be installed to be of the best possible use.

The dimensioning of a TLA generally follows the same criteria as for an arrester in a substation. It is of

great importance that the TLA is designed correctly with respect to energy capability since the stresses on the arrester at lightning are highly dependent on the earthing conditions, presence of shield wires etc. The

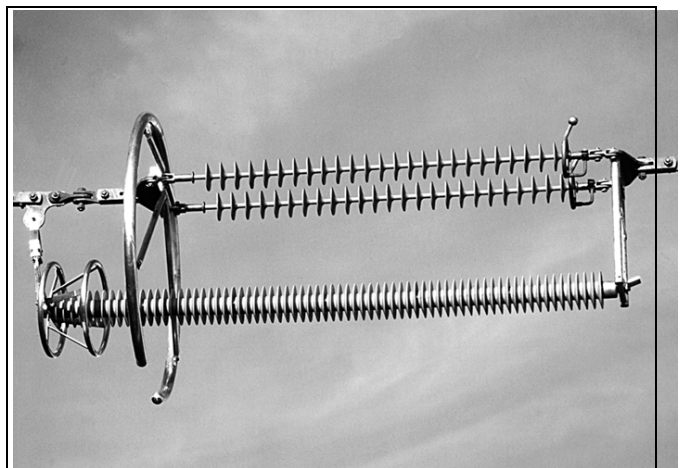


*Figure N: Transmission line arrester with disconnecting device in a 145 kV-network*

selection of the energy capability for TLA has been discussed at several International conferences during the last years [4,5].

### 5.2.1 PRACTICAL USE OF TRANSMISSION LINE ARRESTERS

**figure n** shows how a TLA with polymeric housing has been installed in a 145 kV transmission line. The arrester is secured to the line with standard



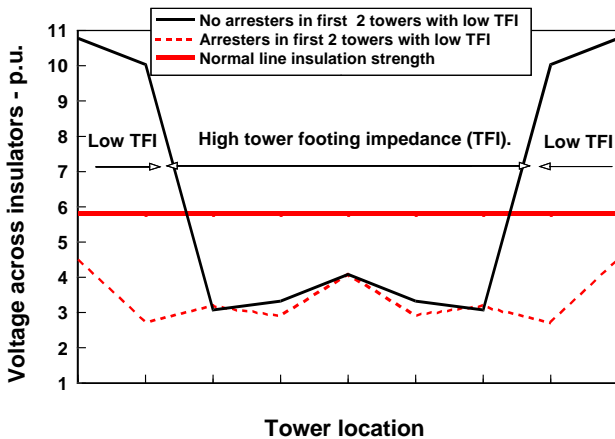
*Figure O: Transmission line arrester for a 420 kV compact line installed below insulator strings. Note the disconnecting device on the high-voltage end at left.*

suspension line brackets. At the bottom of the arrester, a disconnecting device is attached to give an automatic disconnection of the earth connection in the event of an arrester failure due to over-stressing.

Another example is given in **figure o** where an arrester for 420 kV system is installed in a compact line tower.

As an alternative to the disconnecting device, an external gap can be used connected in series with the arrester. At a possible arrester failure the operation can be maintained without a need to disconnect the arrester. An external gap requires, however, a very careful adjustment to the actual tower type, movements of the line due to wind etc.. TLA without series gaps are preferable from the practical point-of-view since such easily can be designed to fit various different tower types.

TLA are preferably installed continuously along the line sections which are exposed to the most problems due to lightning strokes. Along these protected sections, the earthing impedance of the towers can be accepted to be very high without any risk for flashovers. The last towers of the line sections protected by TLA, however, must have adequate earthing conditions otherwise there is a risk that lightning strokes on the protected section will cause flashovers on adjacent towers on the unprotected line sections. This protection philosophy is illustrated in **figure p**.

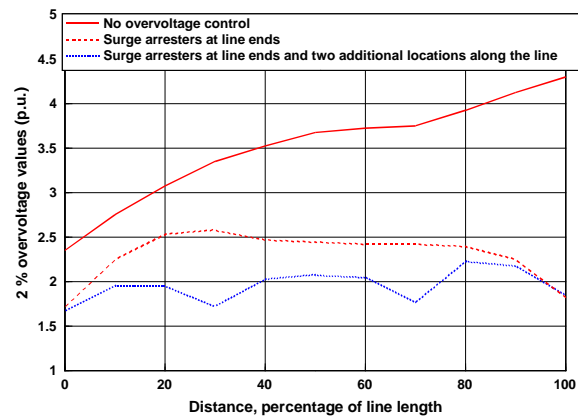


**Figure P:** The effect of transmission line arresters along line section with high TFI, demonstrating the need for arresters at the low TFI towers at the ends of the section.

### 5.3 SWITCHING SURGE CONTROL

For long EHV lines, pre-insertion resistors traditionally are used to limit switching overvoltages at closing and reclosing operations. Surge arresters, as a robust and efficient alternative, could be located at line ends and along the line at selected points. To

locate arresters along the line has previously not been a practical solution due to the fact that only porcelain-housed arresters with high discharge energy capability have been available. Now with the introduction of polymer-housed arresters of IEC line discharge class 3 and 4 up to and including 550 kV systems, a very efficient overvoltage control along long transmission lines is possible which is illustrated in **figure q**.



**Figure Q:** Overvoltages phase to ground by three-phase reclosing of 550 kV, 200 km transmission line with previous ground fault.

## 6. CONCLUSIONS

Existing standards have to be revised to meet necessary requirements from the manufacturers and users regarding arrester designs with polymeric housings.

Utilising polymer-housings results in arrester designs with lower weight and better pollution performance than conventional porcelain arresters. Thermal performance, in general, will be better which could be used to improve protection levels and/or acceptance of higher ambient temperatures above IEC stipulation. A high short-circuit capability could be obtained as well.

Silicon rubber with necessary fillers so far seems to be a better insulator material than EPDM.

It is possible to design polymer-housed surge arresters for EHV voltages and to meet very high requirements on mechanical strength. Special design can give highly improved seismic performance compared to porcelain-housed arresters.

Polymer-housed arresters give new application possibilities like transmission line arresters for

limiting lightning and switching surges on transmission lines.

## 7. REFERENCES

[1] IEC Standard 99-1, "Non-linear resistor type gapped surge arresters for a/c. systems.", 1991-05.

[2] IEC Standard 99-4, "Metal-oxide surge arresters without gaps for a/c. systems", 1991-11.

[3] IEC Committee Draft TC37/154/CD, "Non-linear metal-oxide resistor polymeric housed surge arresters without spark gaps", March 1996.

[4] L. Stenström, J. Lundquist, "Selection, Dimensioning and Testing of Line Surge Arresters", presented at the CIGRÉ International Workshop on Line Surge Arresters and Lightning, Rio de Janeiro, Brazil, April 24 -26, 1996.

[5] L. Stenström, J. Lundquist, "Energy Stress on Transmission Line Arresters Considering the Total Lightning Charge Distribution", presented at the IEEE/PES Transmission and Distribution Conference and Exposition, Los Angeles, September 15-20, 1996.

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