Summary

Metal oxide surge arresters protect electric power systems from overvoltages. The conventional design of metal oxide surge arresters includes a stack of metal oxide varistors and a housing, either a porcelain hollow core insulator or a polymer hollow compound insulator. However, the progress in the polymer technology makes designs possible which are simpler and more cost effective. As an alternative to the use of a polymer compound housing, the active part of the arrester may be kept together by fibre reinforced plastic material wrapped onto it or by a cage of fibre reinforced plastic rods. Among the different polymer material for the housing of wrapped and cage design surge arresters, silicone rubber shows the best ageing and pollution behaviour. Cage design surge arresters with silicone rubber housing offer cost effectiveness, high mechanical resistance, safe burning and short circuit behaviour and excellent long term ageing properties. They are typically used as medium voltage surge arresters, substation surge arresters up to 300 kV and line surge arresters up to the highest voltage levels.

1. Introduction

Electric high voltage power systems are exposed to overvoltages which might overstress the dielectric strength of the equipment used. Overvoltages can be caused by lightning strokes (lightning overvoltages), switching and circuit breaking (switching overvoltages) or certain load flow conditions (temporary overvoltages), the magnitude and time duration of which is shown in Figure 1.
Electric high voltage power systems can effectively be protected against lightning and switching overvoltages by means of metal oxide (MO) surge arresters. The voltage limiting effect of MO surge arresters is achieved by a certain ceramic material, basically a mixture of zinc and bismut oxide, which exhibits an extremely non-linear voltage-current (U-I) characteristic. In Figure 2, the voltage-current characteristic of a surge arrester for an effectively grounded 110 kV system (Highest voltage for equipment $U_m = 123$ kV) is shown together with some typical ratings. As can be seen, there is a broad region of $10^7$ A in between 1 mA and 10 kA where the voltage is limited to values not overstressing the adjacent equipment to be protected.

An overview about the technology of MO surge arresters as well as dimensioning rules are given e.g. in [1]. General technical rules together with type and routine testing procedures are covered in the IEC and IEEE standards [2] [3] [4].

Traditionally, a surge arrester housing consists of a porcelain hollow core insulator as mechanically supporting part protecting the metal oxide varistors (MOV) from the environment. After introduction of fibre reinforced plastic (FRP) and silicone rubber as insulation material for high voltage equipment, new arrester housing design concepts using these materials were established as an alternative to the traditional porcelain housing. While the design and the features of porcelain and tube design polymer surge arresters are explained in detail e.g. in [5] [6] [7], this paper will mainly focus on wrapped and cage design polymer surge arresters.

2. Design and Features of Wrapped and Cage Design Polymer Surge Arresters

Practically speaking, four different design alternatives for metal oxide surge arresters can be distinguished nowadays:

- Porcelain arresters
- Tube design polymer arresters
- Wrapped design polymer arresters
- Cage design polymer arresters
A more detailed classification of polymer surge arresters basing on the construction is given in [5].

Since tube design polymer surge arresters offer outstanding performance in terms of mechanical resistance and short circuit behaviour, they are used particularly in case of extreme mechanical requirements. Typical examples are arresters installed in areas of seismic activity, arresters which are used as a post insulator and arresters for system voltages above about 300 kV, where reliability is a major concern [6] [7].

If there are standard mechanical requirements, wrapped or cage design polymer surge arresters are advantageous over tube design surge arresters simply because of their lower price.

2.1 Wrapped Design Polymer Surge Arresters

The wrapped design polymer surge arrester as shown in Figure 3 utilises a fibre glass cloth impregnated with epoxi resin which is wrapped around the stack of MOV's including the end fittings. After polymerisation of the epoxi resin, the housing material which forms sheds and insulation is moulded directly onto the wrap. Alternatively, pre-manufactured sheds may be slipped over the wrap. As explained in [5], there is a wide variety of wrapped design surge arresters possible.

As with cage design surge arresters, the comparatively simple design of wrapped design surge arresters allows to manufacture cost-effective arresters particularly for medium voltage systems. Here, mainly costs are decisive and reliability plays a less important role as compared to high voltage systems. Consequently, tube design porcelain arresters have almost totally disappeared from the medium voltage distribution systems for new installations and were replaced by polymer surge arrester either of cage or wrapped design [8].

The FRP cloth of wrapped design surge arresters forms a mechanically stable enclosure around the MO elements. In case of an arrester overload and short circuit, the pressure built-up by the arc burning inside this enclosure is limited by its mechanical resistance. If the wrap thickness is chosen too large, a dangerous pressure built-up may occur, violently shattering the housing, whereas a thin wrap results in low mechanical resistance towards external forces. Thus, the thickness has to be balanced between safe pressure relief behaviour and mechanical resistance. Countermeasures against violent shattering such as providing pressure relief slots along the FRP wrap may have the disadvantage of weakening the mechanical resistance.

Typical values for the mechanical properties of different designs regarding an arrester for 170 kV system voltage as an example are summarised in Table 1. As can be seen, the a.m. compromise between safe pressure relief behaviour and mechanical resistance of wrapped design arresters results in a lower mechanical resistance as compared to tube or cage design arresters.

Occasionally, medium voltage surge arresters are arranged in series and parallel connection to form a high voltage surge arrester. By connecting in series, the required rated voltage is achieved and connecting in parallel at the same time results in the necessary energy absorption capability and mechanical stability. Since low cost medium voltage surge arresters
can be used for this arrangement, cost-effective high voltage surge arresters can be produced this way. However, this design bears certain limitations and risks:

The mechanical resistance is comparatively low resulting in little cantilever strength and headload.

Without careful adjustment of the residual voltages of the arresters in parallel, the current distribution will be non-uniform. This may lead to electrical and thermal overloading of the arrester with the lowest residual voltage even if the total current is within the specifications.

The series connection of medium voltage surge arresters includes conductive end fittings or flanges in between the insulating housing material. In case of pollution layers on single arrester units which might occur e.g. on the lower units in the morning hours due to dew close to the ground, surface currents occur flowing over the housing via the metallic parts. This results in a significant field distortion which might cause thermal runaway and failure. This phenomenon generally is a concern for multi unit surge arrester and is the reason why the unit length should be as long as technologically possible.

Figure 4 shows an example for a wrapped design medium voltage surge arrester after overload and short circuit. As can be seen, a collapse of the housing must be taken into account when applying this type of surge arresters to high voltage power systems.

<table>
<thead>
<tr>
<th>Property</th>
<th>Design</th>
<th>Tube design</th>
<th>Cage design</th>
<th>Wrapped design</th>
</tr>
</thead>
<tbody>
<tr>
<td>System voltage in kV</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Static cantilever strength in kNm</td>
<td>14,7</td>
<td>2,8</td>
<td>0,8</td>
<td></td>
</tr>
<tr>
<td>Length in m</td>
<td>1,76</td>
<td>1,77</td>
<td>1,56</td>
<td></td>
</tr>
<tr>
<td>Headload in kN</td>
<td>8,4</td>
<td>1,6</td>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>Deflection in mm</td>
<td>44</td>
<td>173</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Typical mechanical properties of different high voltage polymer surge arrester designs

Figure 4: Medium voltage wrapped design MO surge arrester after short circuit

### 2.2 Cage Design
Polymer Surge Arresters

Instead of using a mechanically supporting FRP layer to accommodate the stack of MO elements, the MO elements themselves can be used as mechanically supporting part. This can be achieved by clamping them in between the end fittings using a cage of FRP rods, which contributes to the name of this design. The silicone rubber insulation is then moulded directly onto the MO elements without any internal gas volume left. Due to the high compressive strength of the MO elements (about 500 MPa) and the high tensile strength of the FRP rods (700 to 1000 MPa), arresters with high mechanical resistance can be produced with this design principle. For high voltage cage design surge arresters, a pre-stress of about 100 kN typically is applied in order to obtain a sufficient mechanical resistance in terms of cantilever strength or headload. This pre-stress is, however, far from utilising the above mentioned strength of either MO elements or FRP rods leaving a convenient safety margin.
As shown in Figure 5 and Figure 6, the cage design can be used for both high and medium voltage surge arresters. The different mechanical requirements in high and medium voltage systems, however, lead to differently pre-stressed FRP rods and thus different solutions for connecting the FRP rods to the end fittings.

Figure 5: Cage design MO surge arrester for high voltage

Figure 6: Cage design MO surge arrester for medium voltage

The MO elements are safely kept in place by the cage together with the high compressive force and they are embedded into the silicone rubber. Thus, the active part is almost perfectly protected from mechanical impact resulting in a high transport safety. Furthermore, cage design surge arresters are of comparatively low weight and thus easy to transport, handle and install.

Since there is a direct contact of the MO elements with the polymer material, heat produced by the MO elements is more easily dissipated through the housing into the environment as compared to tube design surge arrester. This increases thermal stability and allows to utilise more the MO elements with respect to electrical stress.

If silicone rubber is used as the housing material, the only combustible material is the 30% epoxy resin fraction of the FRP rods, which results in a high safety considering the burning behaviour. A cage design medium voltage surge arrester with silicone rubber housing after exposure to AC current 50 A for 30 min is shown in Figure 7. Only development of smoke caused by decomposition of the polymer materials is visible, but there is no development of flames.

Figure 7: Cage design medium voltage surge arrester after exposure to AC current 50 A for 30 min

Among arresters without internal gas volume, cage design surge arresters provide the highest mechanical resistance. As indicated in Table 1, a static cantilever strength of 2,8 kNm is a typical value. In comparison, tube design surge arresters with a static cantilever strength of as much as 50 kNm are available.
In case of electrical overload and short circuit of a cage design surge arrester, the arc can easily burn through the polymer material in between the FRP rods. As opposed to surge arresters with hermetically sealed active part (tube and many wrapped designs), there is only a moderate pressure build-up. Thus, cage design polymer surge arresters offer an inherently safe short circuit behaviour. In Figure 8, a high voltage cage design surge arrester after short circuit test with 65 kA is shown. There is only a crack along the arrester visible, but no ejection of internal parts occurred.

![Figure 8](image-url)

**Figure 8:** High voltage cage design surge arrester after short circuit 65 kA

However, the mechanical performance of cage design surge arresters relies on the internal pre-stress and thus on an intact cage. Since in case of a short circuit the FRP rods might be damaged by the arc heat or broken by the mechanical impulse, there is a certain risk of a collapse of the arrester under external mechanical load. Consequently, as opposed to tube design surge arresters, cage design surge arresters can not be used as post insulators.

### 3. Housing Materials for Polymer Surge Arresters

There are different polymers which are generally suitable as housing material for polymer surge arresters:

- **Silicone Rubber (SR)**
- **Ethylene-Propylene-Rubber (EPR)**
- **Ethylene-Propylene-Diene-Monomer (EPDM)**
- **Ethylene-Vinylacetate (EVA)**
- **Blends and alloys of the a.m. materials, e.g. (EPDM/SR)**

These materials are not used in its chemically pure form, but different additives (fillers, stabilisers, processing aids, curing agents etc.) are required.

There is broad agreement that silicon rubber offers the best long term ageing and pollution performance. Both laboratory tests and field experience show that silicone rubber is superior to all other materials [9] [10] [11] [12] [13]. The main reasons for the excellent properties of silicon rubber are its chemical physical resistance and the effects of hydrophobicity, hydrophobicity recovery and hydrophobicity transfer.

#### 3.1 Chemical physical resistance of Silicone Rubber and EPDM

The chemical physical resistance of polymer materials i.e. the resistance against UV-radiation as well as erosion and tracking is attributed to the chemical bonding strength of the chemical backbone. As shown in Figure 9, the chemical backbone of silicone rubber is constituted by a silicon-oxygen chain (-Si-O-) while the EPDM backbone is formed by a carbon-carbon (-C-C-) chain.

Decomposition of a polymer material occurs if the chemical bonds between the atoms are separated e.g. by radiation, heat or reactive chemicals. Resistance of a polymer against decomposition is characterised by the bonding energy of the different chemical bonds. In Table 2, the
bonding energies of the typical bonds in silicone rubber and EPDM are given in comparison to the energy of UV radiation. Comparing the bonding energy of the silicone rubber backbone (445 kJ per mole) and EPDM backbone (348 kJ per mole) with the energy of 300 nm UV radiation (348 kJ per mole) it becomes obvious that silicone rubber is inherently resistant to UV radiation while the EPDM backbone is destroyed. Of course, EPDM may be protected by UV stabilisers, however, their effect is limited and does only delay decomposition but can not prevent from it. Typical damages to EPDM due to UV radiation are chalking and crazing/cracking [11] [12] [13].

3.2 Hydrophobicity of Silicone Rubber

Hydrophobicity refers to the water repellent behaviour of a surface when it is exposed to humidity. The result is that water on the surface forms individual droplets which are separated by dry zones. This behaviour is very advantageous for high voltage applications, since there is no current carrying conductive path from high voltage to ground which might lead to tracking and erosion. Silicone rubber features the effect of a lifetime, self restoring hydrophobicity and furthermore it is able to transfer the hydrophobicity to pollution layers. EPDM however, loses its initial hydrophobicity after a comparatively short time.

The hydrophobicity of silicone rubber bases on the methyl groups (-CH$_3$) of the material. While methyl groups are non-polar, i.e. they do not have a dipole momentum, water is highly polar and thus repelled. The hydrophobicity transfer of silicone rubber bases on a different effect, the release of low molecular weight (LMW) chains from the silicon rubber, which are comparable to a low-viscosity silicone oil. These LMW chains are able to migrate into pollution layers and make it hydrophobic, too. Astonishingly, there does not seem to be a limited amount of LMW chains in a silicone rubber body, but they seem to be produced from the silicone rubber in a constant equilibrium. Even after strong depletion of the LMW chains the hydrophobicity transfer effect is restored after a certain time [14].

In an attempt to combine the main advantage of EPDM, namely its comparatively low price, with the hydrophobicity effect, silicone rubber was added to EPDM. However, these blends or alloys do only show a good initial hydrophobicity but which is lost later. The dynamic hydrophobicity, i.e. hydrophobicity

<table>
<thead>
<tr>
<th>Chemical bond</th>
<th>Energy (kJ per mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Si - O -</td>
<td>445</td>
</tr>
<tr>
<td>(Silicone rubber backbone)</td>
<td></td>
</tr>
<tr>
<td>- C - H -</td>
<td>414</td>
</tr>
<tr>
<td>- C - C -</td>
<td>348</td>
</tr>
<tr>
<td>(EPDM and Epoxies backbone)</td>
<td></td>
</tr>
<tr>
<td>- Si - C -</td>
<td>318</td>
</tr>
<tr>
<td>Energy of UV radiation (300 nm)</td>
<td>398</td>
</tr>
</tbody>
</table>

Table 2: Bonding Energies of different Chemical Bonds and energy of UV radiation
recovery and transfer, cannot be achieved by this materials.

3.3 Burning behaviour of Silicone Rubber

As opposed to EPR/EPDM, EVA as well as blends and alloys, silicone rubber has an excellent inherent burning behaviour. Silicone rubber passes the test IEC 60707 and UL94 with the highest class V0, i.e. self-extinction within 10 s without development of burning drops. The limiting oxygen index (LOI) is greater than 35%, i.e. to continue burning after inflaming, an oxygen content of more than 35% is required. Since the oxygen content of the atmosphere is 21%, self-extinction can be explained.

The heat release and flame temperature is lower as compared to other organic insulating materials [15]. As a consequence from the bond energies explained in chapter 3.1 and Table 2, the depolarisation energy is very high. Hence, the required temperature for release of combustible decomposition products from silicone rubber is above 300°C. If decomposition occurs, amorphous silicon dioxide (SiO₂) is produced which protects the undamaged material underneath from the flames. Apart from SiO₂, only a very low content of toxic gases is released in case of fire. In tests small amounts of carbon monoxide and dioxide were found. Due to the low fraction of carbon present in silicon rubber, only a low amount of soot is generated which results in a low smoke density [16].

The excellent burning behaviour is inherent to silicone rubber without additional measures. Of course, the burning behaviour of other polymers such as EPR/EPDM or EVA may be improved by flame retardant additives. However, they do not meet the excellent properties of silicone rubber. Furthermore, in case of fire such polymer materials release decomposition byproducts of the flame retardant agents (HCl, HBr, HF, Cyanides, SO₂) which are potentially poisonous and corrosive.

3.4 Types of Silicon Rubber

There are different types of silicone rubber used for high voltage equipment:

- Room Temperature Vulcanising 2 component system (RTV-2)
- Liquid Silicone Rubber (LSR)
- High Temperature Vulcanising (HTV)

Generally, all these silicone rubber types are suitable for the housing of surge arresters and the choice depends on economic considerations rather than technical reasons. While RTV-2 and LSR on the one hand are processed at moderate pressure and temperature, HTV on the other hand needs high pressure and temperature. Consequently, the RTV-2 and LSR processing equipment is significantly less expensive as HTV processing equipment. Together with the fact that RTV-2 and LSR raw material is more expensive than HTV it becomes obvious that the choice of a material is determined by the break even of costs.

4. Application of Wrapped and Cage Design Surge Arresters

Both wrapped and cage design can be used for cost effective surge arresters for medium voltage power systems. In high voltage systems, however, where mechanical requirements are higher as compared to medium voltage power systems, cage design surge arresters are advantageous over wrapped design surge arresters due to their higher mechanical resistance. There are basically two typical applications for cage design surge arresters in high voltage systems, the use as a station surge arrester in regular upright installation and the suspended installation.

The mechanical limits of cage design surge arresters restrict their use as station surge arresters to a system voltage (highest voltage for equipment, Uₘ) of about 300 kV. Above this voltage, due to the required length of the arrester there is only very little permissible headload left which will not be
sufficient in many cases. In addition, there will be a significant deflection at specified headload which might lead to insufficient clearance between phases. Above 300 kV, only the tube design provides the necessary mechanical resistance.

These restrictions do not apply if the arrester is installed suspended, e.g. if used as a so-called transmission line surge arrester (TLSA) [17]. In this case there is little or no cantilever force acting on the arrester and the cage design can be used up to the highest system voltage levels. The application of a cage design surge arrester as TLSA can be seen in Figure 10.

5. Conclusions

There are different design alternatives for high voltage MO surge arresters with polymer housing which include tube, wrapped and cage design. These designs differ mainly in costs, mechanical resistance, burning and short circuit behaviour.

Among the different polymer materials used for the housing of polymer surge arresters, silicone rubber offers the best long term ageing and pollution performance together with an excellent burning behaviour. While EPR/EPDM and EVA as well as blends and alloys of these materials are subject to degradation under service conditions, silicone rubber has an inherent UV resistance together with a life long hydrophobicity and hydrophobicity recovery ability. Even more, silicone rubber transfers its hydrophobicity to pollution layers.

The cost effective wrapped design is mainly found in medium voltage applications due to its limited mechanical resistance and potentially critical short circuit behaviour.

Cage design surge arresters feature cost-effectiveness, high mechanical resistance and inherently safe short circuit behaviour. Thus, this design is suitable for both medium and high voltage applications up to about 300 kV. Above 300 kV system voltage or in case of highest mechanical stresses, cage design surge arresters may not provide the necessary mechanical resistance any more. Thus, for system voltages above 300 kV, tube design surge arresters appear to be more appropriate.

Cage design high voltage polymer surge arresters are suitable for system voltages below 300 kV and standard mechanical requirements if regularly installed in upright position. However, if installed suspended, e.g. as TLSA, cage design surge arresters may be used up to the highest system voltages.

Figure 10: Cage design surge arrester used as transmission line surge arrester (TLSA) in a high voltage overhead power line
6. References


Author address:
Dr. Kai Steinfeld, Director R&D Surge Arresters Siemens AG, PTD H 42, Nonnendammallee 104, D-13629 Berlin kai.steinfeld@siemens.com