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Special Requirements on Gas-Insulated, Metal-Oxide Surge Arresters

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Abstract—**Equipment in high voltage power systems can be protected effectively by metal oxide surge arresters. Basically two different types of surge arresters are used: surge arresters with air insulation using porcelain or polymeric housings (AIS surge arresters) and surge arresters with SF_6-insulation using a metallic housing (GIS surge arresters). The probability of a failure of a GIS surge arrester shall be considerably less than for an air insulated surge arrester. Failures of GIS equipment always will result in major outages and costly corrective maintenance. Potential sources of surge arrester failures are the metal oxide (MO) resistor, insulating parts as fiber reinforced (FRP) rods and partitions and the metal enclosure. MO resistors are not allowed to show any aging und must have a high energy discharge capability. The FRP-rods must be free of partial discharges and must withstand high electrical strength. The metal enclosure must be made of high quality material as well as the manufacturing process shall be of high standard including sufficient testing and final certification. Required routine testing on the completely assembled surge arrester does not suffice rather all parts used must be routine tested in a proper way to avoid failing within the life time of more than 30 years. In case of a failure caused by overloading the destruction must be limited to the surge arrester.**

Index Terms—**overvoltage, metal oxide surge arrester, design, metallic tank, insulating part, failure, quality**

I. Introduction

Overvoltages caused by lightning strokes, earth faults or regular switching actions may endanger the insulation of the electric equipment used in energy distribution and transmission systems. Protection against these lightning and switching overvoltages can be assured by metal oxide (MO) surge arresters. MO surge arresters consist of an active part – a column of MO resistors connected in series – and an enclosure protecting the active part from environmental impact. The enclosure can be a porcelain housing, a composite housing, directly molded silicone rubber or a metallic tank.

The operating behavior of MO surge arresters mainly is given by the nonlinear voltage-current characteristic of the MO resistors permitting low protection levels and stable operation under the most severe conditions at the same time. The protection behavior is not only determined by the protection level of the surge arrester but in addition by the protective zone [5]. That means the protection is becoming better the closer the surge arrester is installed to the equipment. Gas-insulated switchgear (GIS) can be protected by conventional air insulated (porcelain or polymeric housed) surge arresters or by metal-clad, SF_6-insulated (GIS) surge arresters. For some applications, e.g. when the GIS or transformers are fed by long cables, only GIS surge arresters can be used. In any case, GIS surge arresters with metal oxide resistors provide maximum protection for gas-insulated switchgear and transformers, because they can be installed as close as possible to the object to be protected. Due to the low self-inductance of GIS surge arresters, the protection in particular against high rate-of-rise voltages, so called „very fast transients“, is very effective.

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II. General Requirements on GIS Surge Arresters

Both types of surge arresters AIS as well as GIS are affected by stray capacitances to earth resulting in an uneven voltage distribution. While the voltage distribution of AIS surge arresters can be controlled by grading rings up to the highest system voltage of 1000 kV the length of the active part of a GIS surge arrester is limited.

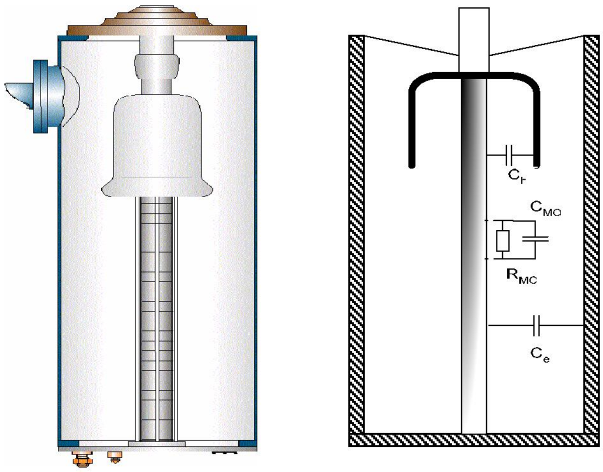

Fig. 1. Design and simplified circuit diagram of a GIS surge arrester

In comparison to AIS surge arresters the voltage distribution along the active part of a GIS surge arrester is highly nonlinear. This is because the earthed metal housing is very close to the stack of MO resistors resulting in very high stray capacitances. Fig. 1 shows the design of a GIS surge arrester and a simplified circuit diagram indicating the nonlinear resistance R_{MO} as well as the capacitances C_{MO} of the MO resistor, C_e to earth and C_h to the grading electrode. Exceeding a certain length of the active part, the nonlinearity of the voltage distribution gets out of hand, resulting in an instability of the surge arrester even when using a grading electrode. Therefore a simple stacking of the metal oxide resistors for a GIS surge arrester is only possible up to power system voltages of 170 kV. A reduction of the length of the active part of conventional type metal-clad, SF_6-insulated surge arresters is realized by using a meandering, three-column mechanical and single-column electrical design. For this purpose electrically highly stressed insulating parts are used.

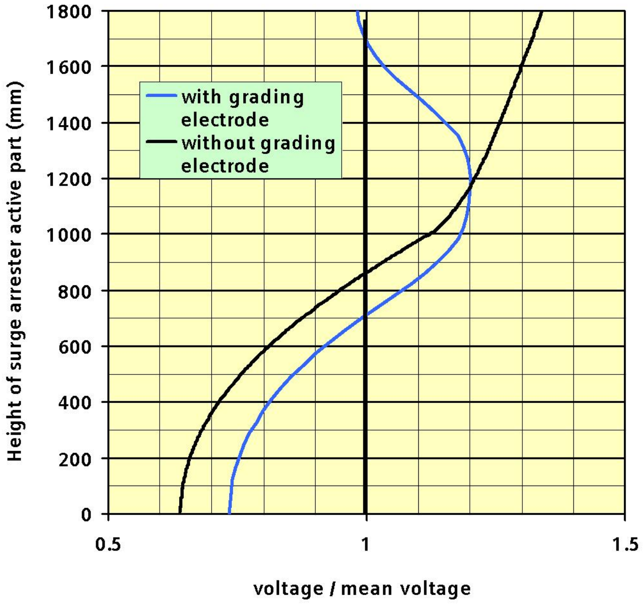

Fig. 2. Voltage distribution of a GIS surge arrester for 550 kV power systems

As an alternative to the conventional design, novel, so called „High Voltage Gradient" MO resistors [1] can be used, having only half of the height of the conventional MO resistors at the same rated voltage. This allows a single-column design of the active part both mechanically and electrically up to 550 kV power systems, omitting the insulating parts. As can be seen from Fig. 2 the voltage distribution of a single-column GIS surge arrester for 550 kV power systems assembled with High Voltage Gradient MO resistors can be controlled by a grading electrode. The voltage drop at the highest stressed MO resistors is about 20 % above the mean value.

III. Special Requirements ON GIS Surge Arresters

It must be pointed out that an arrester failure is a very rare event. While gapped SiC surge arresters failed quite frequently, the failure rates of modern MO surge arresters are comparable with other equipment such as transformers or instrument transformers.

In principle each surge arrester may fail even though the failure rate is far below 0.1 % per year. Failures can be caused by overloading or by insufficient quality of the parts used. The probability of a failure of a GIS surge arrester shall be considerably less than for an air insulated surge arrester. Failures of GIS equipment will always result in major outages and costly corrective maintenance. For this reason only parts of high quality shall be used for GIS surge arresters.

Potential sources of surge arrester failures are:

- the metal oxide resistors
- insulating parts like FRP-rods, insulating plates and partitions
- the metal enclosure.

Demanding requirements have to be met by these surge arrester components:

- MO resistors are not allowed to show any aging behavior and must have a high energy discharge capability.
- FRP-rods and insulating plates must withstand high electrical strength and must be free of partial discharges
- The metal enclosure must be made of high quality material as well as the manufacturing process shall be of high standard including sufficient testing and final certification.

A. *Metal oxide resistors*

The electrical active part of a GIS surge arrester is formed by a stack of MO resistors which can be arranged in a three-column or a single-column design using conventional or High Voltage Gradient MO resistors. The dimensions of conventional and High Voltage Gradient MO resistors are shown in Fig. 3.

Fig. 3. Comparison of conventional and High Voltage Gradient metal oxide resistors (same rated voltage)

The active part must be rated to fulfill certain requirements: it has to provide sufficient protection to the equipment installed, must dissipate the electric energy combined with overvoltages and it needs to remain thermally stable even under the most severe operating conditions. To obtain sufficient electric protection the arrester must limit the voltage across the equipment below its withstand voltage including an appropriate safety margin. With respect to thermal stability the arrester must be rated not to exceed a specific internal temperature after absorption of energy stresses and loading with rated voltage and maximum continuous operating voltage (MCOV) [2]. A suitable design must be tested in an operating duty test according to IEC [4] or IEEE [6] standard.

Protection level and thermal stability mainly are given by the voltage-current-characteristic of the metal oxide resistors. The voltage-current-characteristic of a complete GIS surge arrester for 550 kV power systems assembled with High Voltage Gradient MO resistors is shown in Fig. 4. The lightning impulse protection level is adjusted to the leakage current in order to provide stable operating after energy dissipation.

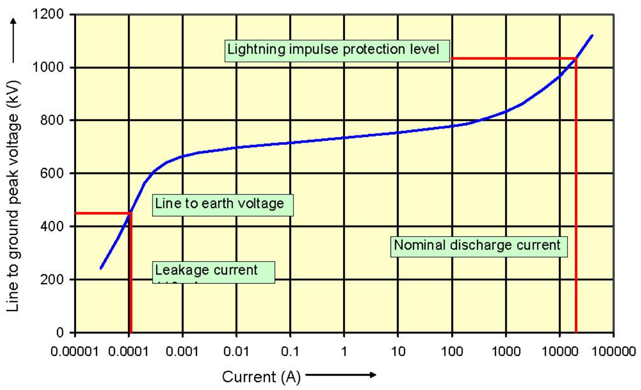

Fig. 4. Voltage-current-characteristic of a GIS surge arrester for 550 kV power systems

Failing of MO resistors may occur by exceeding the specified energy absorption capability or by aging of the voltage-current-characteristic in the leakage current band.

To improve the energy discharge handling of a surge arrester and to reduce the probability of a failure due to extended energy stress the line discharge class should be increased by one. For standard applications in 550 kV power systems a line discharge class of 4 is typically selected, according to the recommendations of the IEC application guide [5] therefore 550 kV-GIS surge arresters are equipped with MO resistors of line discharge class 5.

According to the IEC standard [4] aging of the metal oxide resistors is permitted, however, it must be proven within the operating duty test by elevating the rated voltage as well as the continuous operating voltage of the test samples. The aging behavior of the MO resistors themselves has to be tested in an accelerated ageing test whereas the acceleration factor is given by the temperature of 115 °C. The surrounding medium has to be the same as for the respective application, in case of a GIS surge arrester SF_6. Test voltage has to be the continuous operating voltage increased by the maximum unbalance according to the voltage distribution along the active part of the surge arrester. As can be seen in Fig. 5 the aging behavior can be quite different. Modern MO resistors show a decreasing behavior during the entire test duration even under the surrounding gas SF_6 and increased test voltage. On the other hand there are still MO resistors in the market showing an increasing behavior. To receive a certain amount of safety MO resistors with an aging behavior should not be used, especially for GIS surge arresters.

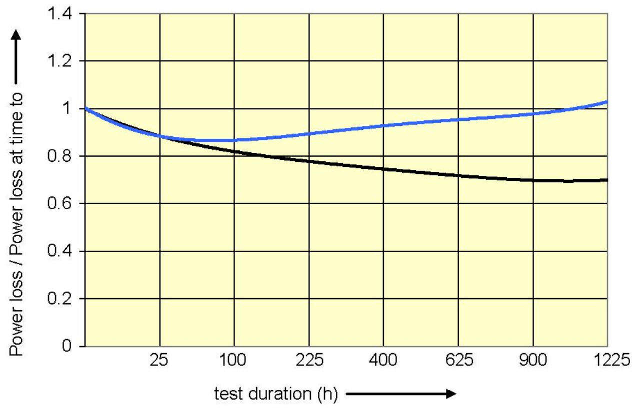

Fig. 5. Aging behavior of metal oxide resistors

The requirements on High Voltage Gradient MO resistors are still higher than on conventional ones regarding the specific energy discharge capability, the dielectric strength of the coating and the thermal stability at the applied continuous voltage. To use all advantages of the High Voltage Gradient MO resistors for the design of a GIS surge arrester the total volume of the active part is reduced using a one-column arrangement only. Keeping line discharge class and rated voltage unchanged compared to the conventional design, less volume results in higher temperatures. To guarantee a stable operating, cooling must happen in particular under higher temperatures presuming an improved leakage current characteristic and temperature dependence. Higher dielectric stress of the MO resistor surface must be handled by an improved collar.

B. *Insulating parts*

Insulating parts can be distinguished into insulating parts within the surge arrester active part itself and a high voltage partition separating the GIS surge arrester from the equipment to be protected.

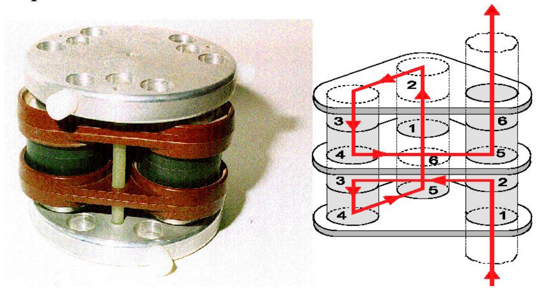

Fig. 6. Design of a GIS surge arrester with a mechanically three-column and electrically single-column arrangement

Using conventional MO resistors surge arresters exceeding a rated voltage of about 170 kV usually are assembled in a mechanically three-column and electrically single-column arrangement as can be seen in Fig. 6. If six MO resistors are used within one stage (two in one of the three columns) the insulating plate between the stages is stressed by the voltage drop of eight MO resistors. The insulating plate (Fig. 7) has to be designed in such a manner that it is free of partial discharges at 1.3 times the continuous operating voltage of the eight MO resistors and must withstand a lightning impulse voltage equal to 1.3 times the residual voltage of the eight MO resistors at nominal discharge current according to the requirements of [4].

Fig. 7. Insulating plate for GIS surge arresters with a mechanically three-column and electrically single-column design

The use of High Voltage Gradient MO resistors allows to get rid of the insulating plates. However, there is still a need to fix the stack of MO resistors by means of fiber reinforced (FRP) rods. High Voltage Gradient MO resistors lead to an enormous electrical stress of the FRP rods especially in the area at the end of the grading electrode. The distribution of the electric potential of a GIS surge arrester for 550 kV power systems is shown in Fig. 8. To avoid long-term failures FRP-rods have to be routine tested to be free of partial discharges.

The partition used to separate the surge arrester gas space from the GIS or the transformer has to fulfill certain electrical and mechanical requirements according to IEC 62271-203 [8]. Electrically the spacer has to be free of partial discharges at 1.2 times the maximum line to earth voltage and must withstand a lightning and switching impulse voltage respectively a power-frequency voltage according to the respective rated voltage of the power system [8]. To ensure mechanically safe operating, partitions have to undergo pressure tests in that way that the bursting pressure tested in a type test has to be in minimum 1.5 times the routine test pressure while the routine test has to be carried out at 2 times the design pressure (maximum operating pressure).

C. Metal enclosure (tank)

Failures caused by overloading can not be avoided. In order to minimize the repair costs the destruction must be limited to the surge arrester. This can be achieved by using sufficient wall thickness of the metal enclosure, a partition separating the surge arrester from the GIS or the transformer and a pressure relief system.

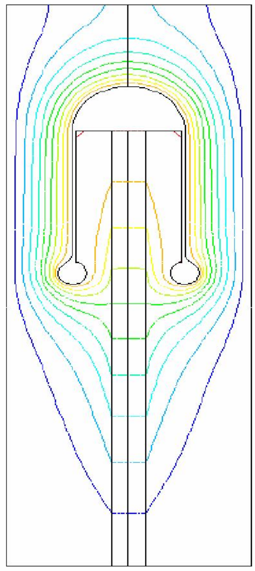

Fig. 8. Distribution of the electric potential inside a GIS surge arrester for 550 kV power systems

Calculations and tests on the metal enclosure are based on the so called design pressure (maximum operating pressure). The design pressure of the tank has to be verified by calculations taking into account the maximum filling pressure of the GIS surge arrester as well as the size and number of bolts used to mount the plates.

Type- and routine-tests applied to the tank depend on the tank material. Materials used for GIS surge arresters are steel and aluminum. Specifications are given in BS EN standards [8]. For steel tanks bursting tests are not required. As a routine test a water pressure test has to be performed at 1.3 times the design pressure. On aluminum tanks a bursting test has to be carried out as a type test with a bursting limit of 5 times the design pressure. As routine tests a pressure test at 2 times the design pressure and a leakage seal test with SF_6 gas at maximum filling pressure have to be performed.

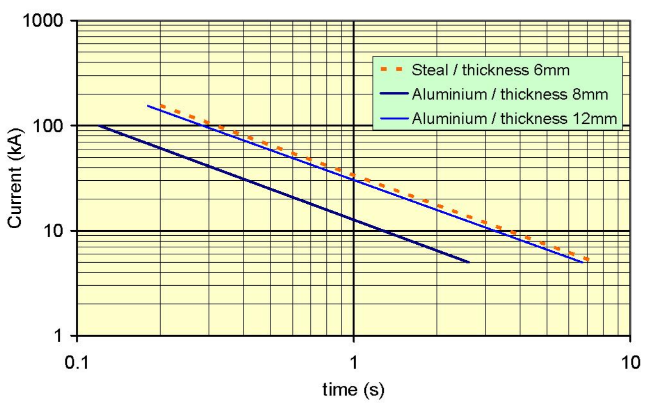

Fig. 9. Burn-through time of GIS surge arrester tanks

The quality of the tanks is demonstrated by certificates of the material used, by approved welders and by stamping and certifying the manufactured and routine tested tanks.

Surge arresters made by Siemens are equipped with a rupture disc which has to operate far below the routine tested pressure values of partition and tank.

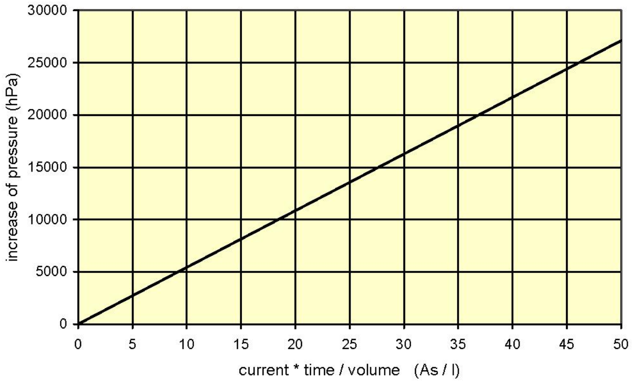

Fig. 10. Pressure increase versus short-circuit current, short-circuit time and gas volume

In case of a surge arrester failure an arc will develop between the surge arrester active part and the earthed tank. To avoid hazardous malfunction a co-ordination between operating of the rupture disc and the tank design (wall thickness) has to be made. Therefore the pressure increase within the tank and the burn-through time of the tank is of high importance. The burn-through time of a surge arrester tank depends on the short-circuit current, the material and the wall thickness of the tank as indicated in Fig. 9.

Fig. 11. GIS surge arresters to protect gas insulated switchgear

Fig 10 shows the pressure increase versus the short-circuit current, the short-circuit time and the SF_6-gas volume of the tank which is given by the formula:

$$\Delta p = \frac{0.542 \bullet I \bullet t}{V} \quad (1)$$

where is: Δp = pressure increase (hpa)
I= short-circuit current (A)
t= short-circuit duration (ms)
V= tank volume (l)

As an example a short-circuit co-ordination is calculated for a GIS surge arrester for 550 kV power systems. Considering a minimum operating pressure of 3000 hPa and a maximum operating pressure of the rupture disc of 10000 hPa resulting in a maximum pressure increase of 7000 hPa, a short circuit current of 65 kA and a tank volume of 750 liters the maximum bursting pressure time of the rupture disc will be:

$$t = \frac{\Delta p \bullet V}{0.542 \bullet I} = \frac{7000 \bullet 750}{0.542 \bullet 65000} ms = 149 ms$$

The burn-through time of a steel tank with a wall thickness of 6 mm at 65 kA short-circuit current is about 0.5 s according to Fig 9. Fault clearing time for the first stage protection is about 0.1 s for currents of 40 kA and above. The short-circuit current will be switched off 50 ms before operating of the rupture disc and about 400 ms before burn-through of the tank.

IV. Routine Testing

Required routine testing on the completely assembled GIS surge arrester according to the IEC standard including a residual and reference voltage test, a partial discharge test and a leakage seal test, does not suffice, rather all parts used must be routine tested in a proper way to reduce the probability of failing within the life time exceeding 30 years.

- Tank: pressure test at 1.3 times (steel) respectively 2 times (aluminum) the design pressure, stamping and certifying; using approved welders and certified materials
- Partition: pressure test at 2 times the design pressure; partial discharge test and power frequency withstand test
- Insulating plates: partial discharge test and power-frequency voltage withstand test
- FRP-rods: partial discharge test
- MO resistors: energy withstand test, residual voltage test, watt loss measurement

V. Applications of GIS Surge Arresters

Nowadays, users of high voltage surge arresters have the choice between different designs. In most of the cases AIS surge arresters are used with housings made of porcelain or polymeric material installed as individual devices or integrated into the equipment to be protected [3]. GIS surge arresters can be considered as an integrated device because they are connected to GIS or transformers predominantly. Because of their highly stressed components and the obliged high quality requirements resulting in low failure probability GIS surge arresters are much more expensive than AIS surge arresters. This is the reason that in cases wherever it is possible AIS surge arresters are used, however the protection behavior of GIS surge arresters is much better.

Fig. 12. GIS surge arresters to protect a transformer fed by cables

But, in some cases only GIS surge arresters can be used e.g. for GIS equipment in certain arrangements or where the GIS is fed by long cables (Fig 11). On this account GIS surge arresters are installed on a transformer using an oil-SF_6 bushing (Fig. 12).

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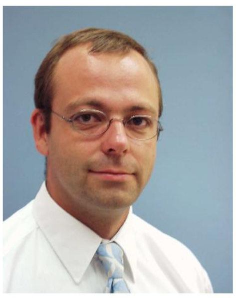
VII. Biographies

Reinhard Göhler was born in Reinsdorf near Hannover, Germany on January 20, 1955. He received the Dipl.-Ing. degree in 1980 in electrical engineering from the Technical University of Braunschweig, Germany.
He joined Siemens AG, Switchgear Works, Berlin in the same year, where he began as a test and development engineer for surge arresters. In 2001 he became director of the sales department for special surge arresters and in 2004 director of the R&D department. He is member of the IEC TC 37 MT 4.



Lars Klingbeil was born in Berlin, Germany on October 26, 1969. Dr. Klingbeil studied electrical engineering at Berlin Technical University and was awarded his doctorate from the TU - Institute of Electrical Power Engineering. After being member of the development group at the Surge Arrester and Limiter Unit at Siemens in Germany, in 2004 he was appointed to the position of Head of Strategy & Marketing of Siemens Surge Arresters worldwide. He is member of the Cigre working group A3.17