INVESTIGATIONS ON MICROVARISTORS AS FUNCTIONAL FILLERS IN INSULATION SYSTEMS FOR HVDC APPLICATIONS

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Abstract: Microvaristors – i.e. small particles of doped zinc oxide with a diameter of 10 to 200 µm – provide a highly non-linear *E*-*J*-characteristic as well as a high relative permittivity ε_r. These particles can be used as functional fillers in silicone rubber, epoxy resin or varnishes. Materials with different switching field strengths from 0.5 to 7 kV/mm can be realized by manufacturers. Application of microvaristors as fillers of polymeric insulating materials transfers the non-linear *E*-*J*-characteristic and a high permittivity to the resulting composite material. Main focus of the investigations presented in this paper is to analyse how such "active" insulating systems can be applied for electric field and potential control in air and gas insulated HVDC systems. Insulators with microvaristor-filled surface layers or surface regions can especially support the flow-off of surface charge carriers, which otherwise would negatively affect dielectric strength. Due to the non-linear characteristic of microvaristors, electric conductivity is only locally increased in the regions of high field stress and accumulated charge carriers. Hence, overall electric losses are lower compared to conventional semiconducting insulating materials having the same electric conductivity. For this contribution, the effects of microvaristor-filled insulating systems were simulated using FEM software tools. Experimental investigations validated the simulation results. Furthermore, the temperature dependence of the *E*-*J*-characteristic was determined and its effect on the insulation system is discussed.

1 INTRODUCTION

High Voltage Direct Current transmission (HVDC) is actually being considered for future long distance power transmission lines. By this technology, transmission losses and power transmission costs are estimated to be lower compared to conventional AC transmission. A European DC super grid is in consideration.

Insulating systems for HVDC applications have to take into account different and additional requirements in contrast to AC transmission systems. The insulators' electric conductivity σ controls the field distribution. Surface charge accumulation on the insulators' surface belongs to the major problems. This charge causes field distortions that reduce the breakdown voltage of the system, and it is very critical for polarity reversal. Especially for compact insulator designs in gas insulated substations the flow-off capability of surface charge carriers is one of the most important design criteria.

Microvaristors are small particles of doped zinc oxide. Typical particle diameters are in the range of d = (10...200) µm [1]. They exhibit a distinct non-linear *E*-*J*-characteristic as well as a high relative permittivity ε_r [2]. Application of microvaristors as filler materials in polymeric insulating materials, such as silicone rubbers, epoxy resins or varnishes, transfers these characteristics to the resulting composite material [1].

These particles have basically a spherical shape, built up mainly from ZnO grains which are typically doped with Bi_2O_3 and other additives. These additives control the particle growth during the sintering process and are responsible for the strong nonlinear *E*-*J*-behaviour [3], [4].

In this contribution, investigations on microvaristors as functional fillers in conventional insulation materials are reported. Due to the transfer of the highly non-linear *E*-*J*-characteristic the resulting material may support a fast surface charge flow-off. In addition, this has to be done with acceptable (low) losses.

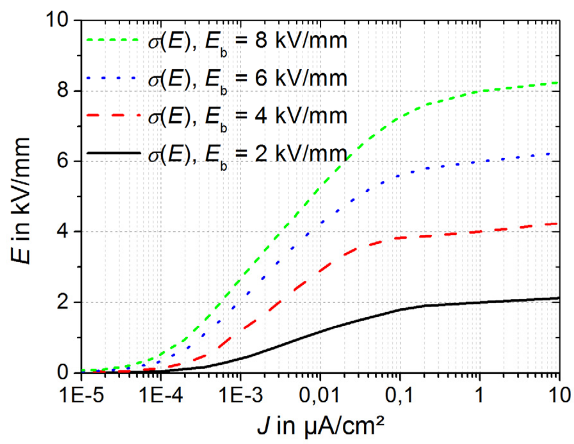

Figure 1: Nonlinear *E*-*J*-curves used for the FEM simulation model

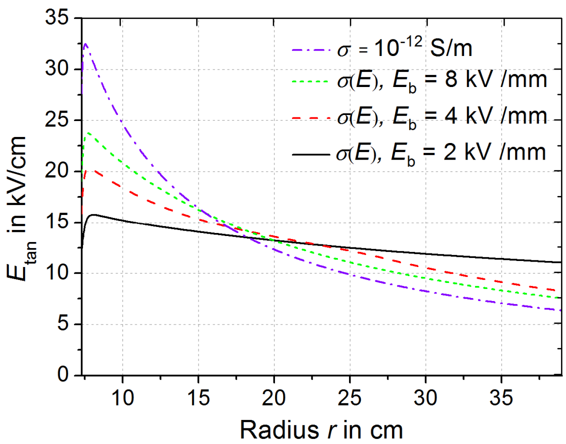

Figure 2: Distribution of the tangential electric field E_{tan} for the E-J-characteristic curves shown in Figure 1 and for constant conductivity $\sigma = 10^{-12}$ S/m

2 FEM SIMULATIONS

The effect of different non-linear E-J-characteristic curves is investigated using FEM simulation software. A simplified model of a GIS spacer insulator is used in order to represent an application with very high electric field stress.

For the calculations, a GIS enclosure diameter of $d = 800$ mm is chosen and a direct voltage of $U = 500$ kV is applied. A characteristic value of microvaristors is its "switching field strength" E_b at which a current density of $J = 1$ µA/cm² is obtained. The simulations were been performed with E-J-characteristics based on measurements on some existing material and then modified by scale factors to achieve different switching field strengths E_b. In **Figure 1** these curves are depicted. More detailed simulation results can be found in [5], [6].

2.1 Field distribution

The effect of different E-J-characteristics on the field distribution along the GIS spacer insulator's convex surface was investigated. For this purpose, the curves from **Figure 1** were used. The microvaristors-filled material forms a 5 mm thick layer on the insulator surface. For comparisons, constant conductivities of this layer were also investigated. The positive effect of the non-linear behaviour of microvaristor-filled insulator layers can be taken from **Figure 2**, where the tangential electrical field as a function of radius r is plotted. The expected field homogenization and its dependence on the switching field strength E_b can clearly be seen. More detailed observations regarding microvaristor-filled GIS spacer field distributions can be taken from [5], [6].

2.2 Surface charge flow-off capability

As mentioned in the introduction, the capability of surface-charge flow-off is one of the main claims in HVDC insulation systems. In [7] surface charge measurements on HVDC GIS spacers are reported, and values up to $\rho_s = 40$ µC/m² have been found. In order to verify the effect of the non-linear E-J-characteristic caused by the microvaristors fillers, several time-dependent calculations were conducted. These calculations were realised with a 2d-model of a simplified HVDC GIS spacer geometry. As a first step, the calculation started without additional surface charge in order to achieve the initial charge accumulation on the insulator surface. The initial charge $\rho = D_{2n} - D_{1n}$ results from $\varepsilon_1/\varepsilon_2 \neq \sigma_1/\sigma_2$ at the boundary from insulator to the ambient SF_6 gas. In the next step the calculation is interrupted. This moment is defined as $t = 0$ s. Now, an additional surface charge is applied to the spacer in the area from $r = 140$ mm to $r = 170$ mm. The surface charge follows a Gaussian distribution with a peak value of $\rho_s = 40$ µC/m² allocated at $r = 155$ mm. Afterwards the calculation is continued and the surface charge along the insulators surface is recorded at discrete time steps. A microvaristor-filled material characteristic $\sigma(E)$ with $E_b = 8$ kV/mm is appointed to the insulator, and alternatively, a corresponding constant conductivity $\sigma = 3.5 \cdot 10^{-12}$ S/m (without additional surface charge, $\sigma(E)$ would have the same conductivity of $3.5 \cdot 10^{-12}$ S/m). The results are depicted in **Figure 3**. A time constant τ is introduced, which indicates the duration from $t = 0$ s to the time instant when 36.79 % of the original charge value is reached:

$$\tau(\sigma(E)) = 28.5 \text{ s}$$

versus

$$\tau(\sigma = \text{const.} = 10^{-12} \text{ S/m}) = 35 \text{ s}.$$

Hence, typical microvaristor characteristics results in improved charge flow-off compared to a corresponding constant conductivity. More detailed surface charge observations can be taken from [6].

2.3 Resistive losses

The advantages in terms of field and potential control and surface charge flow-off capability have been shown. However, resistive losses have to be limited, and noticeable heating of the insulator has to be avoided. A compromise must be found between fast surface charge flow-off and low electric losses.
Due to the non-linearity, the major parts of these losses in microvaristor-filled materials are located in the region of highest electric field stress. For this reason, it is not sufficient to consider the overall-losses of the insulator. Especially near to a triple zone (insulator – gas – conductor) local losses can be very high. The $\sigma(E)$-characteristic with $E_b = 8$ kV/mm leads to resistive loss densities

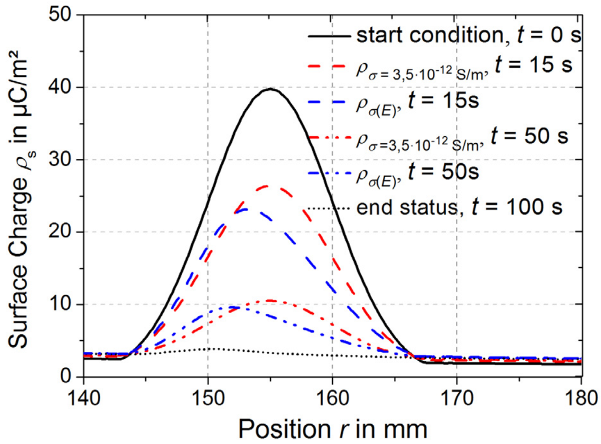

Figure 3: Surface charge flow-off characteristic of a linearly and a nonlinearly conductive insulator

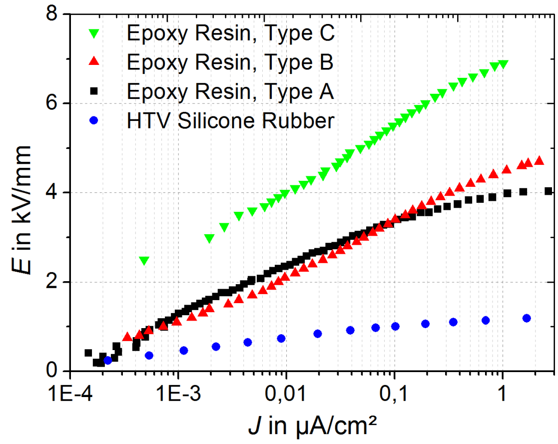

Figure 4: Measured *E*-*J*-characteristic of the HTV silicone rubber and epoxy resin specimens

between 2 W/m³ and 15 W/m³ at the highest stressed regions, whereas the overall resistive losses of this insulator are only 0.07 W and are thus acceptable. Besides, optimized insulator contours will help reducing field stress in the triple zones and hereby reducing resistive heating effects. Detailed investigations regarding resistive losses in microvaristor-filled insulating mediums are described in [6].

3 MEASUREMENTS ON MATERIAL SAMPLES

Several specimens of insulating materials filled with different types of microvaristors and varying filling degrees have been manufactured. The electrical characteristic of these specimens depends on the microvaristor type and concentration, the used polymeric material and the temperature. Epoxy resin and silicone rubber are the two main groups of filling matrices that have been used. The geometry of the specimens is a disc of a thickness of $s = 2$ mm. Depending on the specimen type the diameter is varied between $d = 45$ mm and $d = 120$ mm. All measurements were conducted using guarded electrodes for volume resistivity measurement according to IEC 60093 [8]. The electrodes were pressed onto the specimen by a defined contact force $F = 320$ N. Current measurement is realized by a precision picoampère-meter.

3.1 *E*-*J*-characteristics

The *E*-*J*-characteristics of these specimens were measured at an ambient temperature of $T = 20$°C. In this contribution, only a representative selection is presented. One type consists of HTV silicone rubber filled with microvaristor particles of relatively large diameter (~100 µm). The filling degree was chosen to 75 per cent of weight, and the resulting switching field strength E_b is at about 1 kV/mm. In addition, for high field applications, further test samples of epoxy resin with extremely fine microvaristor particles were manufactured. The particle size varied from 38 µm (d50) to 9 µm (d50). Furthermore, the filling degree was chosen in the range of 79 up to 87 per cent of weight. The *E*-*J*-characteristics of these specimens can be taken from **Figure 4**.

The measured curves illustrate that a wide range of *E*-*J*-characteristic can be achieved by variation of microvaristor type and filling degree. With regard to epoxy resin, microvaristors may be suitable fillers for high field applications, e.g. HVDC GIS spacers.

For example, a suitable solution could be a formulation as for specimen type C. This specimen has a switching field strength of $E_b = 7$ kV/mm and a filling degree of 79 per cent of weight.

3.2 Temperature Dependence

For the following measurements, the test setup was moved into a climate chamber and a temperature sensor was added. The sensor is allocated inside the guarded electrode in order to measure the true specimen temperature.

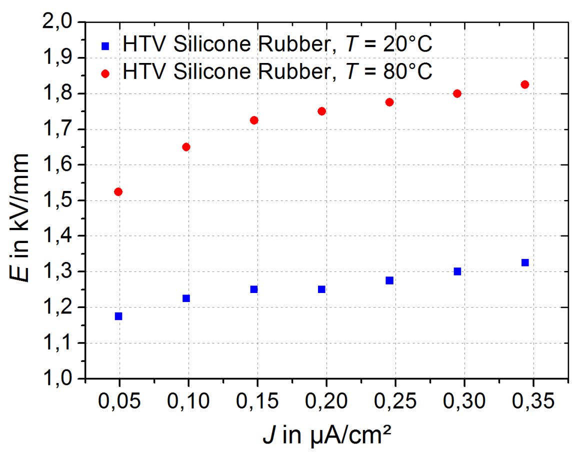

Figure 5: Temperature dependency of the *E*-*J*-characteristic for HTV silicone rubber samples

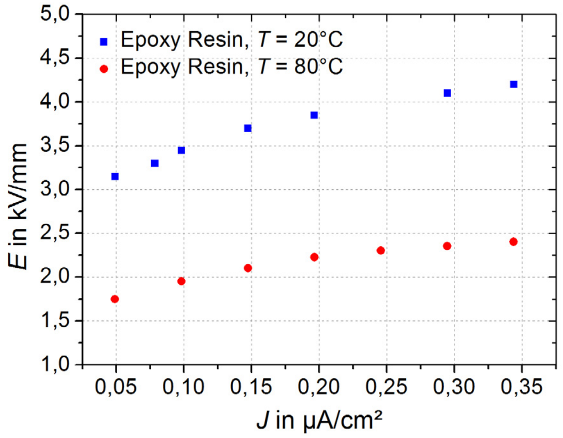

Figure 6: Temperature dependency of the *E*-*J*-characteristic for epoxy resin samples

Measurements on temperature dependence were conducted on microvaristor-filled HTV silicone rubber as well as on microvaristor-filled epoxy resin specimens.

In **Figure 5**, the result for the microvaristor-filled HTV silicone rubber specimen at different temperatures is shown. It can be seen that the electric resistivity of these specimens is increasing with temperature, which is an unexpected and surprising behaviour.

Figure 6 shows the comparable curves of the microvaristor-filled epoxy resin specimens measured in the same test setup. In contrast to the results of **Figure 5**, the electric resistivity of the epoxy specimens is decreasing with temperature, which is considered "normal".

A possible reason for the unexpected different behaviours can be the different thermal expansion coefficients of silicone rubber and epoxy resin in the measured temperature range of 20 °C to 100 °C. At these temperatures, the HTV silicone rubber is above its glass transition temperature T_g. This implies a high thermal expansion rate. In case of epoxy resin, the glass transition temperature T_g is higher than 100 °C. Therefore, thermal expansion below 100 °C is negligible. The high thermal expansion rate of silicone rubber may lead to worse electrical contacts between the microvaristor particles and thus increase resistivity.

4 CONCLUSION

The simulation results have shown the positive effect of microvaristor-filled insulating materials for field and potential control. Particularly, microvaristor-filled insulators may provide a faster flow-off of undesired surface charges in HVDC applications. Local as well as overall electric losses may be acceptable if the switching field strength E_b is properly chosen to achieve a compromise between low losses and good field grading and charge flow-off performance.

The manufactured specimens have demonstrated that microvaristor-filled insulation systems for high field applications can be implemented. Several experimental test setups for further investigations on real insulator configurations are in progress. Furthermore, the material's long-time behaviour has to be determined.

5 REFERENCES

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