IMPROVED PERFORMANCE OF SILICONE RUBBER COMPOSITE INSULATORS BY MICRO-VARISTOR FILLED COMPONENTS

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Abstract: This contribution reports about possible applications of microvaristor filled silicone rubber at composite insulators. It is shown how composite long rod insulators might be equipped with special field control features. Different insulator variations fitted with microvaristor filled sheds or shanks have been investigated. The insulators are dimensioned for U_m = 170 kV and U_m = 420 kV. Different variations of the two types were tested for their a.c. and d.c. behaviour under artificial rain. Special designs with double-layer-sheaths are presented. In these investigations the insulators with microvaristor filled silicone rubber components showed interesting properties limiting partial discharges at the insulator. The suitability of microvaristor filled silicone rubber for application both in the sheds and in the sheath is checked visually and by a daylight-UV-camera and discussed based on these positive results. A further important issue is the thermal reaction of the insulators, checked by an IR camera.

1 INTRODUCTION

Improving the performance of equipment in electrical power systems by new materials is an ever challenging task in electrical insulation engineering. Also for composite long rod insulators such approaches are important in order to reduce electrical stress on their surface and to provide better performance under polluted conditions. A problem of high-voltage insulators is the extremely uneven voltage distribution along their length. This is mainly caused by the unfavourable combination of low self capacitance and high earth capacitances. Common measures to improve the potential distribution on high voltage insulators are shield electrodes at the metal end fittings. They help avoiding discharges on the insulator surface directly at the high voltage side. Yet another problem is dry band arcing under rain and pollution. The to date's established insulator technology is the result of both long field experience and modern field simulations. But field simulations also show that new materials with special properties such as high permittivity or a nonlinear voltage-current-characteristic may improve the voltage distribution. Microvaristor filled silicone rubber exhibits such properties. Microvaristors are small particles of doped zinc oxide (ZnO). They have the same distinct nonlinear *U*-*I*-characteristic and a high relative permittivity like large ZnO varistors. Microvaristors allow transfer of these nonlinear properties to a compound based on silicone rubber, for example. For these studies, a high-temperature-curing-(hct-) silicone is used. **Figure 1** presents the non-linear electrical behaviour of the applied microvaristor filled silicone rubber. This characteristic is measured on a small plate type sample. It must be noted that there are big differences between the *E*-*J*- (and *U*-*I*-, respectively) characteristics at direct and alternating voltage stress. The d.c. characteristic is easier to measure and very useful for evaluation of physical properties such as temperature dependence. Furthermore, the d.c. characteristic is important to understand the insulator's behaviour in d.c. applications. A voltage source generates a sinusoidal voltage without harmonics for the measurement of the a.c. characteristic. This is necessary to separate the total a.c. current into a capacitive and a resistive component. The first one is not only caused by the permittivity of the silicone rubber (ε_r = 2.3). The high permittivity of the ZnO varistors ($\varepsilon_r \approx$ 100...500) is transferred to the composite material, depending on the degree of filling. In this case, the filled silicone rubber has a resulting dielectric constant of $\varepsilon_r \approx 13$. This property is necessary for the originally intended field grading application in cable accessories.

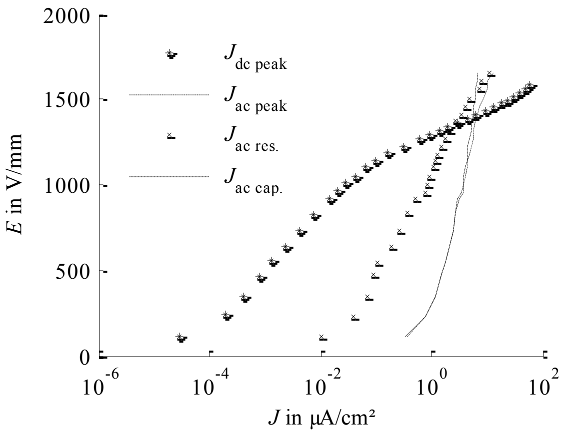

Figure 1: *E*-*J*-characteristic of the microvaristor filled silicone rubber separated in d.c. and a.c.

It is not really necessary for the insulator application considered here, because the earth capacitances dominate such large structures. The resistive part of the current is caused by the distinct nonlinear conductivity of the microvaristors ($\alpha = d\ln(E)/d\ln(J) \approx 40$) [2]. An important characteristic value of a microvaristor filled silicone rubber is the switching field strength E_b, which is the field strength necessary to obtain a current density (at d.c.) of 1 µA/cm². In this case, E_b is 1200 V/mm. At this characteristic field strength the microvaristors become increasingly conductive. From Figure 1 it is evident, that the capacitive component dominates the total current in the pre-breakdown region below the switching field strength, E_b. The microvaristors are becoming increasingly conductive in the breakdown region, and the resistive current component then increases rapidly with only minor increase of the field strength.

Currently, there are only cable terminations with a PE matrix on the market, which make use of microvaristor technology [1]. Thus also the applied microvaristor filled silicone rubber was developed especially for field grading elements in cable accessories [2] [3]. Other applications are still under investigation. But no composite insulators with semi-conducting housing materials are available to date. However, positive effects of a semi-conducting glaze on porcelain insulators are known [4]. By this technology it is possible to affect the voltage distribution along the insulator under rain and polluted conditions and to optimize the “dry band arcing” performance. But a problem has been the production with reproducible electrical properties. These problems are not expected to appear with microvaristor filled silicones because they can be manufactured easily in a well controlled and highly reproducible process. So they could be favourably applied to improve the flashover performance of the insulator through linearization of the voltage distribution. This aspect will become even more important for (UHV-) HVDC transmission lines where it is not possible to affect the voltage distribution by capacitive measures such as shielding electrodes. Furthermore, the microvaristor filled silicone rubber could form a bypass to dry bands on a polluted insulator surface, thus reducing or even avoiding dry band arcing.

2 MICROVARISTOR FILLED COMPOSITE INSULATORS

First investigations on composite insulators with microvaristor filling in the sheds and in the sheath of the shank have shown some promising results for a.c. and d.c. applications [5] [6] [7]. The investigations were performed with different insulator types for two different highest voltages of equipment, $U_m = 420$ kV and $U_m = 170$ kV. The microvaristor filled silicone rubber is also used both

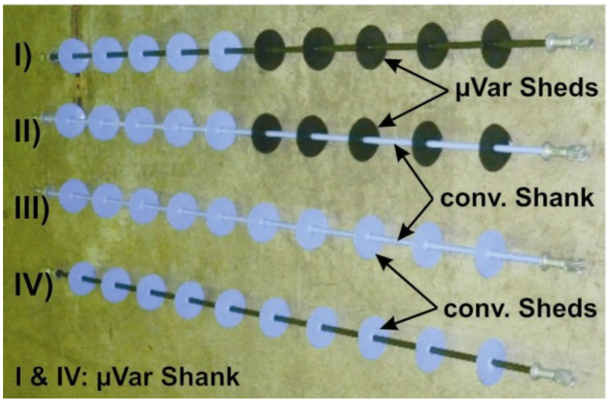

Figure 2: Example of four investigated insulators for U_m =420 kV [6]

for the shank sheath and for the sheds. As the insulator is of modular design, sheath and sheds can be made from different materials. An example for $U_m = 420$ kV is shown in **Figure 2**. The insulators have an arcing distance of $s = 2800$ mm and a creepage distance of $l_c = 3910$ mm. The number of only ten sheds was chosen to achieve stronger dry band arcing effects at the bottom side of the sheds. The conventional silicone rubber is blue, whereas the microvaristor filled silicone rubber is black. These test specimens are manufactured in the same manner as the conventional insulators. In case of insulator I and II only the five sheds on the high-voltage end are completely filled with microvaristors. This is justified by the fact that the high electrical field strength, which is necessary to make the microvaristors become conductive, is only present at the h.v. end of the insulator. Comparison of the different insulators was first of all performed by electrical tests, beginning with alternating voltage application under artificial rain up to $U = 600$ kV. First of all the development of the discharges with increasing voltage was checked visually. The result was quite interesting: partial discharges were significantly suppressed for all three insulators with microvaristor filled elements. However, further tests at lightning und switching impulse voltages (also under artificial rain) show some disadvantages of the completely filled sheds because they were punctured during the test. Since insulator IV passed these tests without any objections, this is the most promising design. For this reason it is used for further tests on shorter insulators ($U_m = 170$ kV). The short length of these insulators allowed additional d.c.-tests under artificial rain [7] in the laboratory, which gave the same positive results, as shown in **Figure 3**, which is a comparison of a conventional insulator and a microvaristorfilled one at $U_{d.c.} = 430$ kV. As mentioned before, both insulators have a reduced creepage distance ($s = 1300$ mm, $l_c = 2200$ mm). It is clearly visible that the discharges in the dry regions under the sheds of the microvaristor filled insulator are considerably reduced. The physical effect is described in 3.2.

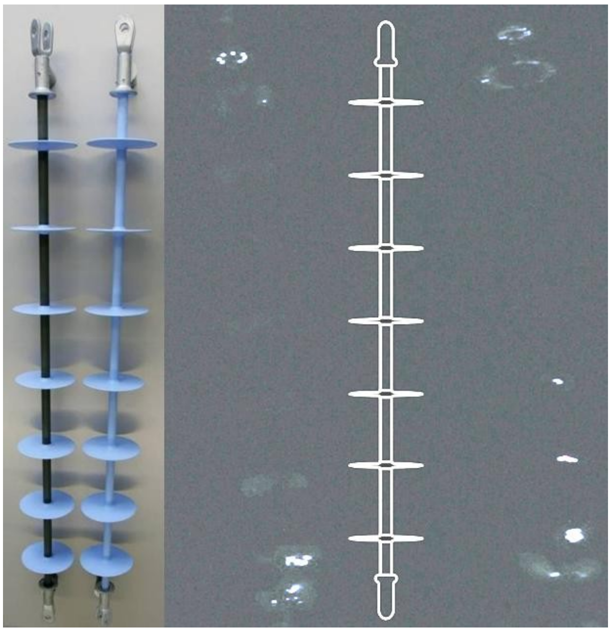

Figure 3: Test result of a d.c.-test at $U_{d.c.}$ = 430 kV

Further investigations with thermovision techniques show neither at a.c.- nor at d.c. voltage stress any heating of the microvaristorfilled layers.

3 A.C. AND D.C TESTS UNDER ARTIFICAL RAIN

3.1 Test setup

According to earlier publications, insulators of U_m = 170 kV are manufactured. Because the microvaristor filled silicone rubber has not the tracking and erosion resistance required for outdoor applications, a new design had to be developed. The shank is fitted with a silicone-double-layer to achieve sufficient outdoor resistance. The inner layer, directly on the GRP core consists of microvaristor filled silicone rubber. It is protected by an additional outer conventional silicone rubber layer. **Figure 4** shows the scheme

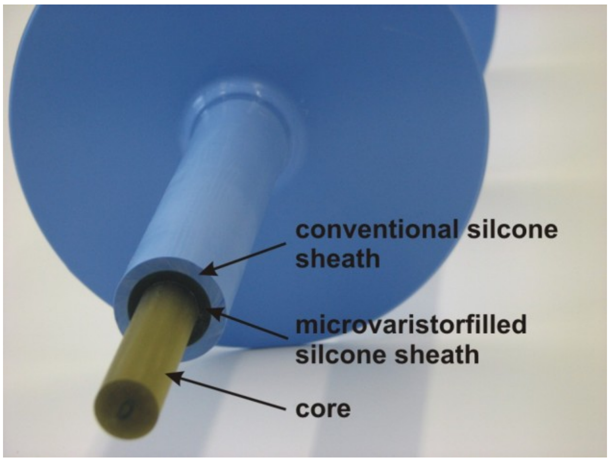

Figure 4: Scheme of the investigated double-layer-shanks.

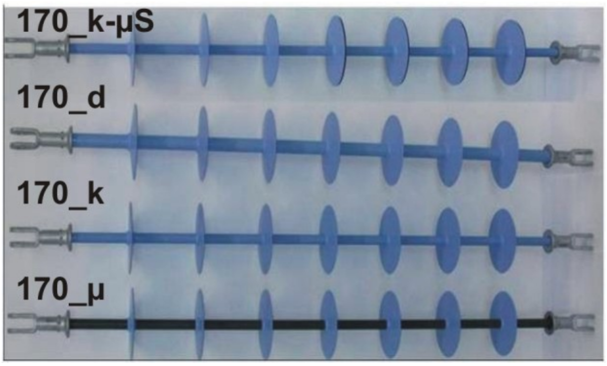

Figure 5: The four tested insulators

of the double-layer shanks. This insulator (170_d) is compared to a conventional insulator (170_k) and to another one with a microvaristorfilled shank (170_µ). A further conventional insulator is equipped with microvaristor filled silicone rubber plates applied to the underside of five sheds (170_k-µS). Due to the lower filling degree of microvaristors, these plates have higher mechanical flexibility for the application under the sheds. But the consequence is a worse electrical characteristic with a higher resistance. The four test specimens are shown in **Figure 5**. Their arcing distance is s = 1300 mm and their creepage distance l_c = 2200 mm. There are only ten sheds instead of seventeen in order to ensure a better observability of the developing discharges. These are investigated visually in the dark test laboratory and with a UV daylight camera. The tests are performed at a.c.- and d.c.-voltage under artificial rain.

3.2 Test results and discussion

The results of the performed tests correspond to former studies [5] [6] [7]. According to these studies, the results of designs 170_k and 170_µ could be approved with the a.c. test under artificial rain. The result on insulator 170_d is quite impressive as it also shows significant reduction of discharges across the dry regions underneath the insulator sheds. Two representative examples of the measurement methods are shown in **Figure 6** and **Figure 7** for direct voltage $U_{d.c.}$ = 430 kV. Figure 6 shows a visual observation of the reduced discharges on the insulators, whereas Figure 7 illustrates the discharges under daylight, recorded with the UV camera. This camera allows very good localization of the discharges, however, their magnitude cannot be evaluated. The conductive rain causes wet layers on the upper side of the sheds and along the shank, resulting in shifting potentials. In the case of the conventional insulator there is a large voltage drop across the dry region underneath the sheds. The high electrical field stress exceeds the breakdown strength of the surrounding atmosphere, and electrical discharges would appear. Both test methods show that microvaristor filled silicone rubber elements

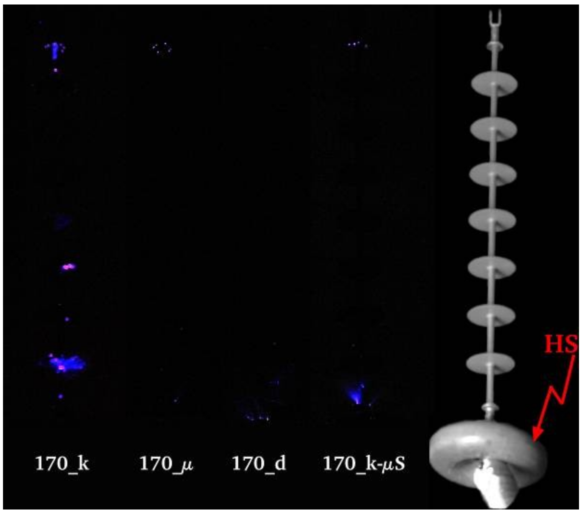

Figure 6: Different discharge-intensities on the four investigated insulators recorded at $U_{d.c.}$ = 430 kV and artificial rain (photography in the dark test hall; the daylight insulator photo on right hand side is for comparison and localization purposes)

(170_µ, 170_d, 170_k-µS) reduce partial discharges across the dry bands on the insulator surface. Insulator 170_d with the double-layer silicone rubber sheath is especially remarkable as it does not show discharges though the microvaristor filled layer is not in direct contact to the outer surface. Summarizing, the arc reducing effects are also present under d.c.-voltage application. Furthermore, evidently no galvanic contact is necessary for the function of the microvaristor filled silicone rubber sheath. The microvaristor filled layer is only capacitively coupled to the insulator surface. The electrical displacement between the layers occurs due to transient effects such as discharges, moving water drops and flowing surface charges. The microvaristors resistance decreases due to the impressed external electrical field, which allows a current flow bypassing the dry band on the surface. As a consequence, the electrical field is reduced there locally, stays below the breakdown field strength, and discharges are avoided. But in particular, there is no global current through the insulator sheath necessary to ensure the field grading effect of the microvaristors. Thus the effect appears only at the high-voltage end, because the electrical field strength is the highest there. Further measurements of the field distribution along the insulator have confirmed this model, showing that the global electrical field distribution is only partially affected. But along the whole insulator length there is no difference between a conventional shank and the the microvaristorfilled shank recordable. This is also the case for applied a.c.-voltage.

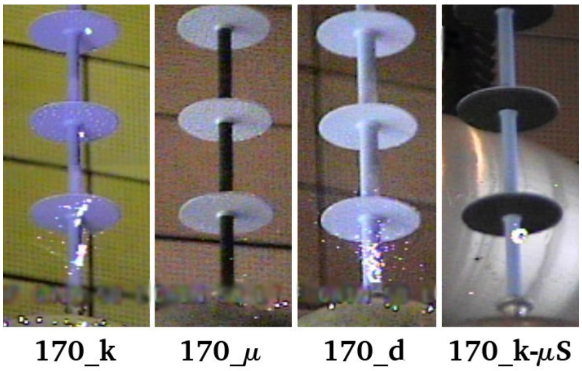

Figure 7: Different discharge-intensities at the four investigated insulators recorded at $U_{d.c.}$ = 430 kV and artificial rain with a UV daylight camera

Using simulation tools helps understanding the field limiting effect of the microvaristors. Conductive layers on long rod insulators can be calculated with new simulation tools [8]. Both the microvaristor filled silicone rubber and the conductive rain layer on the insulator surface can be simulated as 2D models with a non-linear conductivity. By this approach it is possible to simulate the large space surrounding the insulator under consideration of the non-linear material parameters, present only in thin layers, very efficiently. These simulations have now partly confirmed the experimental findings in such a manner that the voltage drop underneath the sheds is reduced [9].

Another important issue is the performance in weather ageing tests to evaluate the long term behaviour of the insulators with the microvaristor filled components. One method for testing outdoor and long term applicability is a weather ageing test under salt fog according to standard [11]. For this test six insulators of U_m = 170 kV were manufactured. The first one is the conventional insulator with shank and sheds of conventional silicone rubber. The second one has a microvaristor filled shank sheath with conductive contact to the metal end fitting. Each insulator carries 17 sheds. They provide an arcing distance s = 1385 mm and a creepage distance l_c = 3400 mm. Two further insulators are according to Figure 3. Finally, two other insulators are equipped with microvaristorfilled sheds similar to the ones shown in Figure 2. The insulators are vertically mounted in a 50 m³ salt fog test chamber. The applied test voltage is U_p = 99 kV. This value relates to 34.6 mm creepage distance per kV in case of the first two test specimens. According to the standard requirements, the test duration is 1000 h. First of all, neither a discharge nor an unacceptable high leakage current occurred at the test specimens. Both insulators with seventeen sheds passed the test with any objections. There was no indication of any tracking and erosion. But the insulator with the microvaristor filled shank and only seven sheds shows some critical erosion at the grounded end. The two insulators with the microvaristorfilled sheds did not pass the test, because they were punctured during the test, caused trough a too high current flowing through them axial. These findings justify further studies with insulator variations containing the described double-layer-sheath. But the design of microvaristorfilled sheds has to be optimized.

4 CONCLUSION AND OUTLOOK

Microvaristorfilled silicone rubber enables new possibilities for long rod insulators. It supresses surface discharges on dry bands in a classical test under artificial rain. They do not decrease the lighting impulse withstand voltage. Furthermore was no unacceptable heating of the microvaristorfilled silicone sheaths recordable. Using insulators with a double-layer-sheath combines the positive effects of microvaristorfilled silicone with the well-known excellent outdoor resistance of conventional silicone rubber. Especially for d.c. applications are these possibilities quite important, to design a reliable stress control system of critical electrical field strengths. But microvaristor filled silicone rubber is not designed for outdoor applications. Tracking and erosion resistance, in general, is not sufficient. Therefore, a design has been developed with an additional conventional silicone rubber layer, covering the microvaristor layer completely. This design is able to fulfil outdoor application requirements. Corresponding tests are planned for the second half of the year 2011. In order to use microvaristor filled sheds, an optimized design is necessary as well, because sheds as investigated so far are not applicable [6]. A reduction of the switching field strength to $E_b = 500$ V/mm is planned to investigate to which extent it is possible to also affect the distribution of the overall electrical field. Especially for d.c.-applications is it quite important to find methods of field control. The reported results suggest that the electrical loses along the insulator will be acceptable.

5 ACKNOWLEDGMENTS

The authors would like to thank Mr. Michael Hagemeister for delivering test material. This work is financially supported by “Arbeitsgemeinschaft industrieller Forschungsvereinigungen e.V. (AiF)” under number 15455 N.

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