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COMPOUND SEMICONDUCTORS AND APPLICATIONS

Electro-Thermal Coupling for Simulation of 52 kV Polymeric Bushing with Nonlinear ZnO Microvaristor Under Different Environmental Conditions

Bushings are considered as one of the main components of power transformers, a key element of the transmission network. Recently, bushings with composite housings have been adopted because of their advantages over ceramic bushing, e.g., reduced weight, reduced explosive hazard and better performance under polluted conditions and under seismic activity. However, excessive electric field intensity can originate tracking and erosion effects on the insulating material affecting the withstand capabilities of the bushing. This paper investigates the electric field distribution coupled with temperature distribution on a 52 kV polymeric bushing to determine any vulnerable areas. The simulation evaluates the electrical and thermal stress reduction in these identified areas by introducing ZnO-microvaristor material, as a possible solution to mitigate these damages. A suitable bushing design using this field grading material is proposed for effective stress control near the flange ground terminal to offer the manufacturers additional confidence for applying novel insulating materials.

Keywords:
Polymeric bushing, Non-linear field grading composites, Stress control, Finite element method, ZnO microvaristor.

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INTRODUCTION

Polymeric materials have been widely used for outdoor insulation in transmission and distribution systems for economic and technological reasons. Compared to analogous ceramic insulation systems, polymeric insulation provides a substantial weight reduction, less fragile properties and better performance under pollution [1]. However, composite insulation materials suffer from degradation and aging issues from surface partial arcing due to localized high electric field magnitudes. The organic nature of polymeric materials determines a vulnerability to degradation and aging under various electrical, environmental, mechanical and thermal stresses [2]. Therefore, it is important to design the polymeric insulation system without any high electric stress areas under all possible in-service environmental conditions.

Recently, the utilization of resistive field grading materials using specific ceramic powders for stress control has been introduced [3,4]. Developments and improvements in the manufacture of ZnO microvaristors and compounding with silicone materials provide a promising solution for reducing electric fields across polymer insulating surfaces [5]. This resistive non-linear electric field grading material based on ZnO microvaristors displays high field-dependent conductivity characteristic, which allows redistribution of the electric field, hence prevents localized field enhancements. Cardiff University High Voltage Research Team [4-6] showed how the formulation of ZnO microvaristors can offer the possibility to adjust nonlinear switching parameters such as field switching thresholds, especially in HV applications including high voltage composite insulators.

In this paper, a polymeric bushing with field grading material has been investigated to identify optimal parameters that impact electric field distribution on the bushing surface. These include thickness, length, position and the switching parameters of field grading material such as initial conductivity, non-linearity coefficient, and field switching threshold. The simulation work was performed using COMSOL Multiphysics 5.5 and 2D axisymmetric models [7]. The simulation results show the impact of the optimal parameters field grading material in reducing the high electric stresses present in the initial bushing design.

ZNO MICROVARISTOR PROPERTIES

ZnO microvaristors are semiconducting particles having high nonlinear voltage-current properties. These may be utilized as a filler to produce nonlinear features to the insulating matrix, impart its nonlinear characteristics and form field grading composites. They are utilized for stress control in several HV applications, like power modules [8], induction motor stator coils [9] bushings [4], cable accessories [3], and composite insulators [4-6]. Moreover, micro-scaled electroceramic particles exhibiting highly nonlinear electrical properties like ZnO varistor in high voltage arrester applications have been developed [10].

A Scanning Electron Microscope (SEM) picture of such material is shown in Fig. 1 [5].

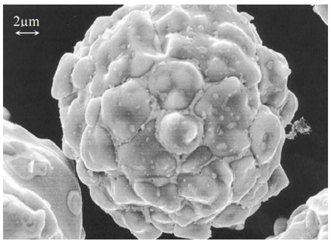


Fig. 1. Microvaristor structure viewed using SEM [5].

COMPUTATIONAL MODELLING

Design of polymeric bushing with non-linear resistive field grading material

Medium voltage distribution polymeric bushings consist of three main parts: the insulation housing body including the weather sheds that are made of silicone rubber insulation, the energised HV copper conductor core onto which the polymeric housing is molded, and an aluminum flange (ground terminal).

A simplified 52 kV silicone rubber bushing was investigated in this work. The key components of this bushing are shown in Fig. 2.

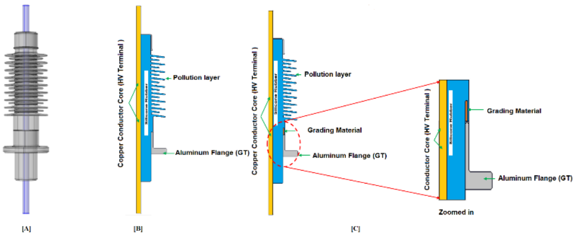


Fig. 2. 52 kV polymeric bushing (A) assembled bushing parts (B and C) computational axi-symmetric model of the proposed design adopting ZnO microvaristor material (details in C).

The pollution layer over the polymeric bushing surface is assumed to be uniform with 0.5 mm thickness [4]. The material properties of the polymeric bushing with ZnO microvaristor material are summarized in Table 1.

Materials	Relative Permittivity ε_r	Conductivity σ [S/m]
Air background	1	1×10^{-14}
Silicone rubber	4.3	1×10^{-15}
Conductor core	1	15.998×10^{7}
Aluminum flange	1	5.96×10^{7}
Transformer oil	2.2	9×10^{-12}
Pollution layer	81	1×10^{-6}

Table 1. Material properties adopted for polymeric bushing modelling.

The electrical conductivity of the nonlinear field grading material based on ZnO microvaristor exhibits a high degree of nonlinear behavior, and it can be expressed by the exponential function as given in (1).

$$\sigma(E) = \sigma_o \left[1 + \left(\frac{E}{E_o}\right)^{\alpha} \right] \tag{1}$$

Where $\sigma(E)$ is the non-linear conductivity of field grading material, σ_0 is the low field conductivity, E_0 is the intensity of the electric field, E_0 is the field switching threshold, and α is the nonlinearity coefficient. The dielectric constant of the field grading material is assigned as ε_r [5].

Furthermore, the switching threshold value identifies the electric field magnitude at which the field grading composite electrical characteristics start to vary, changing very quickly from very low-loss insulator state to fairly-good conductor operation mode. This threshold magnitude is a crucial parameter for achieving efficient field grading in different HV applications. Figure 3 shows an example of conductivity-field characteristic illustrating the point of switching threshold E_0 . Beyond the switching threshold value, any slight rise in the magnitude of the electric field leads to a significant rise in the conduction current.

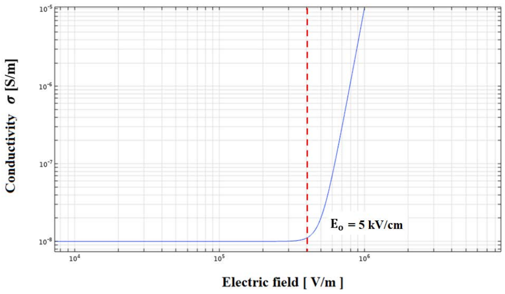


Fig. 3. Field-dependent conductivity of non-linear field grading material with switching threshold value.

Finite Element Analysis

In this study, field computations and modelling have been carried out by the commercially available FEM package COMSOL Multiphysics 5.5 [7]. Because of the symmetrical shape of the polymeric bushings, we adopted an axi-symmetric model with Electric Currents (EC) interface to decrease memory requirements and processing time [7]. The polymeric bushing model in Fig. 2 was implemented for the simulation study. The simulation of this simplified configuration under pollution condition shows that the most non-uniform electric field distribution with highest magnitudes is near the flange ground terminal and thus reflects the worst-case scenario.

The applied voltage on the HV conductor core is phase-to ground value equivalent to 30 kV at 50 Hz, while the flange terminal is grounded. The axial symmetric line in the r-z plane was assigned as the polymeric bushing symmetry line. This study is performed under dry and clean, and pollution conditions, according to conditions specified in IEC 60507 standard [12]. The mesh density is assigned manually to improve the accuracy, especially near the critical regions of the flange ground terminal, as shown in Fig. 4.

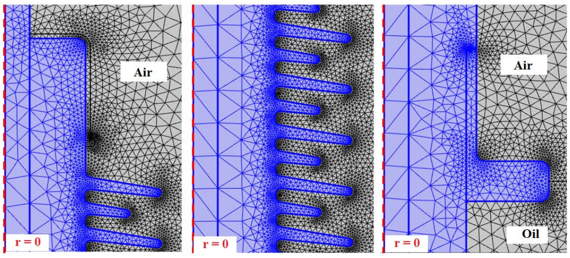


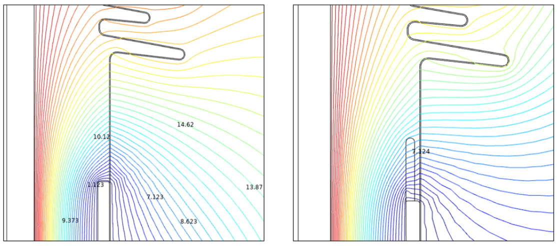
Fig. 4. Mesh discretisation of polymeric bushing domain.

SIMULATION RESULTS AND DISCUSSION

Equipotential lines along polymeric bushing surface with and without ZnO microvaristor material under uniform wet pollution conditions

The simulation results have shown that the different thicknesses and lengths of grading material, as well as the switching parameters of the field grading material have a crucial role in obtaining effective field grading along the polymeric bushing surface. In this simulation, the evaluated performance of the new graded bushing was obtained with the following parameters of field grading material: length and thickness of grading material; L=30 mm and T= 4 mm respectively, switching field threshold E_0 = 5e5 V/m, conductivity at point of threshold σ (o)= 1 x 10^{-8} S/m, coefficient of non-linearity α = 10. These values offered a better performance near the flange ground terminal compared to other values found in literature. Figure 5 shows the computed equipotential lines on the polymeric bushing model when the surface is wet pollution conditions without and with the addition of grading material.

As can be seen on the figure, the application of the non-linear field grading material clearly changes the distribution of the equipotential lines near the flange ground terminal. Such redistribution suppresses field enhancements along the bushing surface in the region of the grounded flange. Of particular interest is the triple junction region where the polymeric material, air and the metal of the flange meet. The field is significantly reduced to magnitudes below air ionisation threshold, hence suppressing initiation of electrical discharges on the bushing surface.



[A] Wet Pollution Without Grading Material

[B] Wet Pollution With Grading Material

Fig. 5. The equipotential lines along the polymeric bushing surface without (a) and with grading material (b) under wet polluted condition.

Electric field distribution along the polymeric bushing surface with and without ZnO microvaristor under wet pollution condition.

Figure 6 illustrates the tangential of electric field distribution over the polymeric bushing leakage distance without and with grading material. The polymeric bushing with ZnO microvaristors shows a significant reduction of the tangential electric field distribution agreeing with the observation from equipotential lines plot. The tangential component of the electric field with the grading material is more uniform along the surface, preventing extreme electrical stress at the triple junction point near the flange ground terminal.

Figure 7 shows that the maximum electric field magnitude decreases from 0.57 kV/mm to 0.39 kV/mm near the flange ground terminal, representing a 31.5 % electric field reduction.

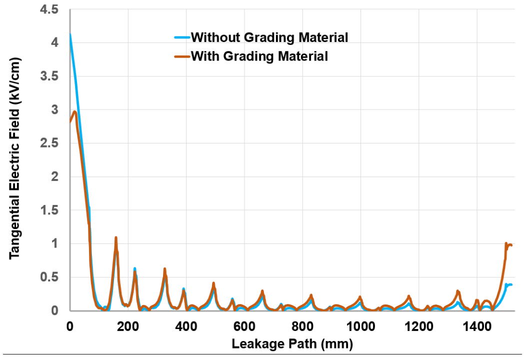


Fig. 6. The distribution of the tangential electric field over the polymeric bushing leakage path without (in blue) and with grading material (in brown).

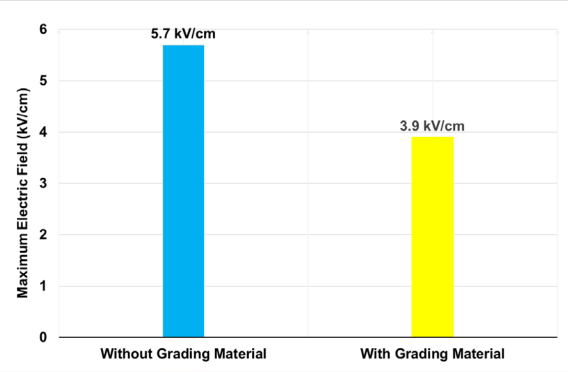
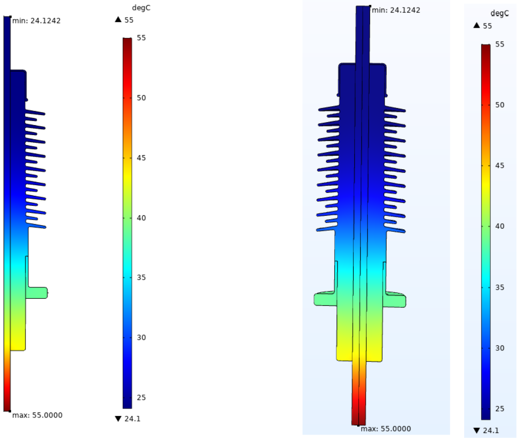


Fig. 7. The maximum electric field magnitude near the flange ground terminal of the studied polymeric bushing.

Temperature distribution of polymeric bushing without ZnO microvaristor material

As a bushing is operating, a portion of the current through the conductor of the bushing dissipates power and converts the losses into heat, and this raises the temperature of the bushing [13]. The chemical nature of the insulator can change if the bushing is overheated, or if it is exposed to high temperatures for prolonged time. This situation leads to changes in the physical bushing electrical properties and accelerates its degradation and ageing rates [13]. It was shown that the Hot Spot Temperature (HST) of a bushing is inversely proportional to its lifetime [14]. Moreover, calculating the HST and the temperature distribution of the bushing is thus very useful in identifying the best design and performance of the bushing.

Figure 8 shows the two- and three-dimensional temperature distributions on the studied polymeric bushing under the rated bushing current of 1250A. The 3D model has been developed for further simulations with a non-uniform pollution layer non-axially symmetrical, not presented in this work. The highest temperature obtained from the simulation of the polymeric bushing is 55°C, which is inside the oil tank in the vicinity of the copper conductor. The reason for different temperature distributions on the bottom and top of the polymeric bushing is due to the top part being surrounded by ambient air and cooled by convection, while the bottom of the polymeric bushing is located in the transformer oil tank, at 80°C at full load conditions.



(a) (b)

Fig. 8. (a) Two-dimensional temperature distribution in the polymeric bushing (b) Three- dimensional view of the polymeric bushing temperature distribution (°C).

Effect of current magnitude on the polymeric bushing temperature distribution

The temperature distribution on the conductor under different current magnitudes is calculated to identify the effect of the current magnitude on the magnitude and location of the HST. The application of 700, 1250, 2000, and 2500 A currents to the composite bushing, have been investigated and the results are shown in Fig. 9.

The temperature distribution is evaluated from the top region (air-sided part) to the lower region of the transformer (oil-sided part). As seen in Fig.8, the temperature distribution along the conductor and hence the bushing length is nonlinear and non-constant. As expected, the temperature value for each location appears to be affected by the current magnitude. It can be observed in Fig. 9 that higher increases are seen in the high current range.

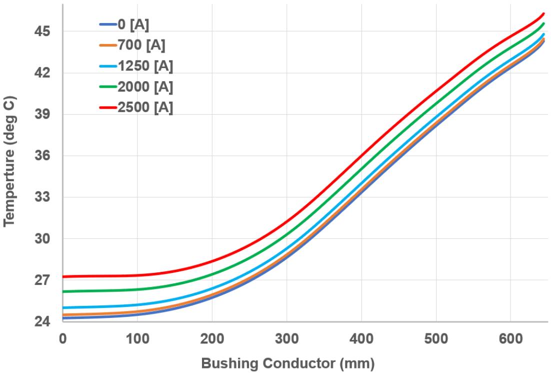


Fig. 9. Temperature distribution on the conductor for different currents (°C).

CONCLUSION

The influence of non-linear resistive field grading material based on ZnO microvaristors for stress control on a 52 kV polymeric bushing is investigated. The proposed graded material performance exhibits best performance compared to the typical polymeric bushing, and the electric field enhancements at the triple junctions are successfully reduced. The maximum electric field magnitude reduced from 5.7 kV/cm to 3.9 kV/cm near the flange ground terminal, representing a 31.5% electric field reduction. These promising results indicate that it is possible to reduce the risk of corona and surface electric discharge initiation over the polymeric bushing surface, reducing the possibility of dry bands formation and arcing, which may eventually lead to tracking and erosion of the polymeric bushing surface. Furthermore, the temperature distribution and heat analysis are essential investigation for such bushings. The bushings can have a reduced lifespan and are prone to malfunction due to the highest heat load resulting from power dissipation in the inner conductor. The temperature distribution and hottest spot temperature of the bushing are impacted by this power dissipation, along with other factors such as the flowing current, conductor material, and insulation material. a two-dimensional temperature distribution of the bushing was obtained. The hottest spot on the conductor, located near the flange, was then identified. Next, the current through the conductor was varied in four discrete values, and the temperature of the conductor was measured and the impact of the current on the hottest spot temperature was determined. It was concluded that increasing the current led to a slight increase in the temperature of the conductor and in the hottest spot, and no significant thermal stress was observed in the studied polymeric bushing.

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