

Analysis of the Electric Field and the Potential Distribution in Cavities Inside Solid Insulating Electrical Materials

T. Seghir^{*1}, D. Mahi¹, T. Lebey², D. Malec²,

¹ Materials Laboratory, Electrical Engineering Institute, Amar Thelidji University of Laghouat Algeria

² Electrical Engineering Laboratory, University of Paul Sabatier, Toulouse France

* PO BOX 37G, Laghouat (03000) Algeria, t.seghier@mail.lagh-univ.dz

Abstract: Solid extruded polymeric materials such as crosslinked polyethylene (XLPE) are widely used in the electrical insulation of underground high voltage power transmission cables. However, the electric strength of the high voltage cable is affected by the presence of cavities (voids) in the insulating part. During service, when the insulation is subjected to electrical, mechanical and thermal stresses, these cavities may create a larger discontinuous region. As embedded gases and XLPE have different permittivities (respectly 1 and 2.3), the potential distribution is not equally distributed and may exceed the breakdown voltage of the gas. On the other hand, under high voltage operating conditions, trapped or low mobility electrically charged species within the bulk can give rise to space charge build up.

This paper treats the combined effect of space charge and cavities on the electric field, potential and temperature distribution within solid insulation. The values of their magnitudes in cavities are calculated, enabling us to envisage if partial discharges appear in these weak parts. The model is a 3D stationary linear FEMLAB model in electrostatics and heat transfer by conduction mode.

Keywords: Electric field, space charge, high voltage power cable, cavities.

1. Introduction

The existence of small gas-filled cavities in solid dielectrics is very difficult to avoid during the manufacturing process. Under certain conditions (the development of partial discharges), these cavities can be critical for the life of equipment operating at high voltage levels.

The study of electric field distributions in and around insulating structures is of considerable interest for electrical engineers when designing equipment that operate at very high voltage

levels. The peak stress value in an insulating system is an important parameter to control because it influences discharge initiation and propagation. Field distribution is distorted inside the insulator due to the presence of gap cavities. These voids may be formed during the manufacture, installation or operation of the high voltage system. Such voids are filled by low pressure gases and these gases have a lower dielectric strength compared to the rest of the system insulation. Consequently, these voids are points and may have the highest electric field stress which initiates the partial discharges in the system.

Our work deals essentially on the numerical resolution of the distribution of the potential and electrical field along the heterogenous insulation's cable, The insulation wrap, in which we calculate the distribution of the electric field and the temperature, is limited by two semiconductor layers that constitute the radial boundaries of our domain. Consequently, the radius of the conducting core in addition of the thickness of the conducting layer represents the high voltage electrode. The second semiconductor layer on the insulator at the earth side takes the null potential value. This constitutes the limit conditions of our problem. This study deals with the thermal behaviour of a unipolar cable of 30 kV as nominal high voltage. The dimensions of this cable permit the establishment of an electrical field of 4.15 kV/mm, this value is far to be critical for the material. This cable is an underground one, and submitted to the interior temperature of the soil. This temperature which we estimate to be equal to 15°C as a mean value constitutes the first limit condition for the cable. The second condition is the temperature created by Joule effect within the conducting part of the cable. This one is estimated equal to 90°C [1].

2. Theory

2.1 Space charge

The space charge was used originally to describe the electronic charge that accumulates, in the insulating material, between the cathode and the anode. Space charge can result from a range of phenomena, but the most fundamental are :

1. The combination of a current density and spatially inhomogeneous resistivity as given in Cartesian coordinates by

$$\zeta(x) = J\epsilon \frac{d\rho(x)}{dx} \quad (1)$$

Where ζ is the space charge density, J is the current density, ϵ is the absolute dielectric constant, and ρ is the electrical resistivity.

2. Ionization of species within the dielectric to form heterocharge.
 3. "Charge injection" from a stress enhancement; however, such space charge will often be too localized to be detected.
 4. Polarization in structures such as water trees.
- Among these mechanisms, the first two probably account for the majority of space charge detected, and, among them, the first typically dominates [2].

2.2 Cavities and partial discharges

Cavities are considered as a weakness in extruded insulations and, depending on their size and location, may be the sites for PD which eventually lead to the failure. Small voids appear in the insulation as a "natural" result of the manufacturing process.

However, in 1975 Kageyama *et al.* [3] counted $\sim 10^6$ cavities/mm³ ranging from 1 to 5 μm , about ten years later Ballet *et al* [4] published that the normal manufacturing cooling process for dry-cured XLPE cables led to a density of 10^3 to 10^7 cavities/mm³ in the same size range. If a cavity does not exist in a macroscopic sense it may be initiated during the system life by the application of the electrical stress, this case may correspond to a local stress due to the accumulation of charges.

Larger voids could also appear as a result of imperfections in the insulation material or abnormalities in the extrusion process. These voids are extremely harmful to the insulation and should be detected before the equipment goes into service.

3. Model

The model is a 3D stationary linear FEMLAB model in electrostatics and heat transfer by conduction mode.

3.1 Field and temperature equation

The governing equations for the FEMLAB model are (2) and (3):

$$-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = \rho \quad (2)$$

$$-\nabla \cdot (K \nabla T) = Q \quad (3)$$

Where ρ is the free charge density, ϵ_r is the relative permittivity, ϵ_0 permittivity of vacuum, K is the thermal conductivity, Q is the heat source.

3.1 Geometry and mesh

In this study, we chose a cable of high voltage of real size. The thickness of the insulating part is 11.3 mm. The geometry model is three dimensional (3D) and is shown in Figure 1. It consists of three sub domains: The insulation material, the cavity domains which is located in the middle of the insulation, and the part of insulator which contains a space charge.

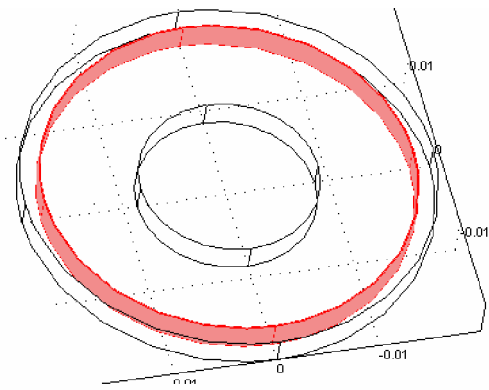


Figure 1. The geometry of the model

A mapped mesh with 86520 tetrahedron elements is used. The mapped mesh is chosen instead of an unstructured mesh to make it easier to control the element density in the thin cavity surface. A picture of the mesh is shown in Figure 2. Figure 3 shows the model in the postprocessing mode.

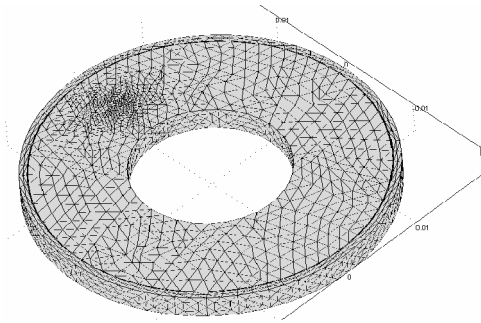


Figure 2. Mesh with 86520 tetrahedron elements

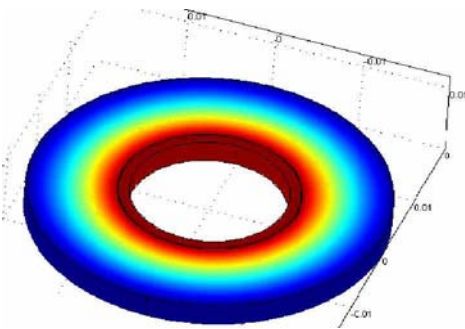


Figure 3. Model in the postprocessing mode.

4. Results and discussion

In a first step, we represent in the figure 4 the distribution of the temperature along the insulating part of the cable. It is noticed that the temperature is not affected by the presence of the cavity and of the space charge. It is clear that the value of the temperature within the cavity is approximately 322 °K.

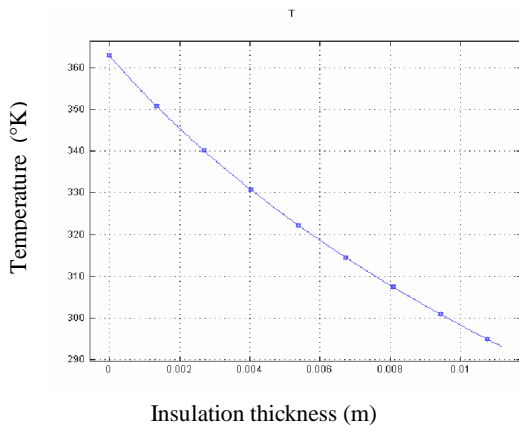


Figure 4. Distribution of the temperature along the insulator.

Now consider that before the cable service, the cavity occlude gas is atmospheric pressure. Let $P_0 = 1$ bar and the room temperature T_0 . Once the cable is in service, a temperature gradient is set in permanent regime. To this fact, and according to the cavity position, the occlude gas pressure will differ atmospheric pressure, regarding the ideal gas law:

$$P = \frac{T}{T_0} P_0 \quad (4)$$

Where P and T are the pressure and the temperature in the cavity respectively in a given position. Once the pressure P is determined, we calculate the critical field of Paschen necessary to the apparition of the partial discharges in the cavity.

$$E_c = K \cdot P^{0.7} \cdot d^{-0.3} \text{ (kV/mm)} \quad (5)$$

Where P is the pressure inside the cavity (mmHg), d is the radius cavity (mm), and K is a constant equal to $8 \cdot 10^{-3}$. In our case, for cavity of $40 \mu\text{m}$ and regarding the equation (5), the critical field of paschen is $E_c = 2.33 \text{ kV/mm}$.

The graphical representation of the potential and the electric field sparking cavity and along the insulation for different value of space charge ($1, 0.1, 0.01 \text{ C/m}^3$) are given in figure 5 and 6.

We present also, in the same figure, the distribution where there is no space charge in the insulation. It is clear that the distribution of the potential and the electric field is affected by the presence of space charges.

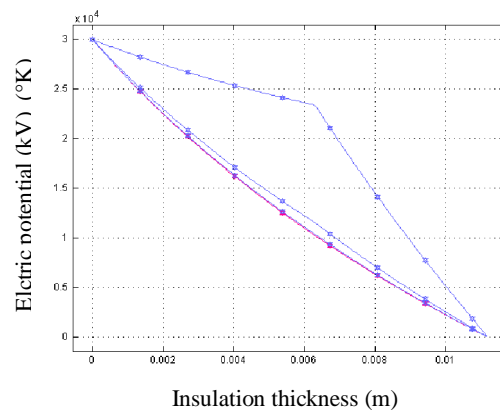


Figure 5. Distribution of the potential along the insulator.

Figure 5, in blue line, shows that the increase on potential depends strongly on space charge. The red line is the potential in the absence of space charge.

Figure 6 shows that the electric field in the sparking cavity decreases weakly despite the large increase of the electrical field in the external part of insulation. Consequently, we intended to treat the case where the space charge is located in different position in the insulation.

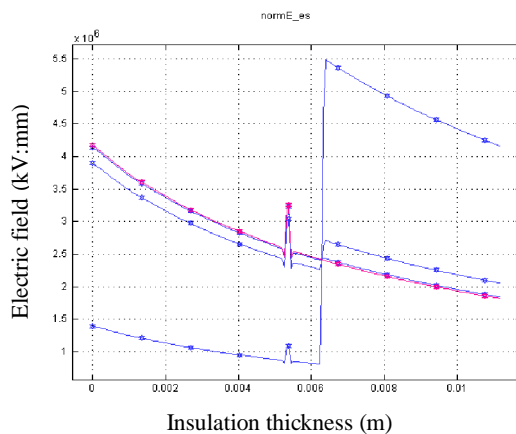


Figure 6. Distribution of the electric field along the insulator.

To qualify the apparition of the partial discharges, in the cavity, we have introduced a different space charge, at a different position in the insulation. In the figure 7, we plotted the distribution of the maximum electric field in the cavity and the critical field of Paschen.

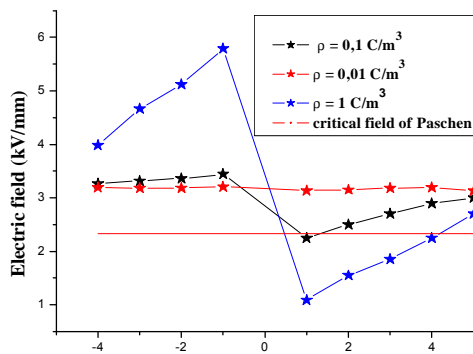


Figure 7. Electric field within cavity.

Figure 6 shows that, for a space charge of 1, 0.1, and 0.01 C/m³, the critical field of Paschen is reached. In the case of a space charge of 0.1, 0.01 C/m³ and contrarily to what is expected, the critical value of breakdown field is practically reached for all the positions of the space charge. In the last case, where $\rho = 1$ C/m³, partial discharges occur when a space charge is located in the part of insulation, between the cavity and the high voltage electrode. The field in the cavity decreases if one move away from the cavity towards the electrode low voltage, and remains always lower than the critical field. The presence of space charge is, in this case, is more harmful

5. Conclusion

This work allows us to treat the combined effect of space charge and cavities on field, potential and temperature distribution within solid insulation. The values of such magnitudes, in cavities, are calculated, what enabling to envisage if partial discharges appear in these weak parts. In the case of a space charge of 0.1, 0.01 C/m³ and contrarily to what is expected, the critical value for the field is practically reached for all the location of the space charge. In the last case, where $\rho = 1$ C/m³, partial discharges occur when a space charge is located in the part of insulation, between the cavity and the high voltage electrode. The presence of space charge close to the high voltage electrode is therefore the most harmful.

6. References

1. A. Lacoste, L. Gausse, R. Michel, câbles isolés, *technique de l'ingénieur*, Vol. D II4, D641, pp 47-57, (Paris 1984).
2. S. Boggs, A Rational Consideration of Space Charge, *IEEE Electrical Insulation Magazine*, Vol. 20, No. 4, pp 22-27(2004).
3. S. Kageyama, M. Ono and S. Chabata, Microvoids in Crosslinked Polyethylene Insulated Cables, *IEEE Trans Pas*, Vol 94, pp. 1258-1263 (1975).
4. E.H. Ball, H. W. Holdup, D. J. Skipper and B. Vecillio, Development of crosslinked Polyethylene Insulation for UV cables, *CIGRE*, Paper 21-01 (1984).