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Study of Electrical Constraints within Cavities in High Voltage Cables

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Abstract: This paper studies the electrical constraints within an XLPE insulated cable containing micro-cavities. The purpose of this work is to determine by simulation the distortions caused by micro-cavities on the electric field distribution in the insulating layer of cable. The computation method used to determine the electric field is based on numerical resolution of Laplace equation using the finite element method. The threshold of partial discharges ignition in gaseous cavities contained in XLPE insulation of 30 kV cable is studied. The computation of the critical field by approached formula of Paschen permits us to elucidate the harmfulness caused by a cavity according to its size and its position.

1. Introduction

Cross-linked polyethylene is principally used for cables of underground distribution lines, because of its excellent characteristics: dielectric strength, low dielectric permittivity and loss factor, good dimensional stability, solvent resistance and thermo-mechanical behavior [1, 2].

Observations made by electronic scanning microscope reveal the presence of gaseous cavities in the XLPE material. These cavities are the direct result of water steam penetration in the insulator during the cross-linking process and also due to the incorrect extrusion and cross-linking operations [1]. The sizes of the cavities are between 1 μm and 20 μm and their distribution in the cable is more important in the region located at three quarter of the insulators thickness going from the core [3].

The noticeable effect of these cavities is to make heterogeneous the insulation in the area where they happened and cause a distortion in the electric field distribution. The amplitude of the distortions in the gaseous cavities depends essentially on the permittivity of the retained gas, on the cavity shape and its position with respect to the core. Due to this fact, the electric field constitutes the most important stress. Indeed, when the electric field intensity inside the cavity reaches the limit value of the gas dielectric rigidity, and accordingly to Paschen law, partial discharges occur. In order to solve this problem, we have developed a numerical computation to resolve Laplace's equation and we have used the Finite Element Method (FEM) with COMSOL multiphysics software.

2. Model finite-elements of the cable

2.1 Finite-Elements Method

The finite elements method is a numerical technique used to get a precise solution to problems of multi-physical types. In this article, the finite elements method is put under COMSOL multiphysics and we use the electrostatic model. The principle of the FEM and the different steps of the simulation under the COMSOL environment are represented by the chart in "Fig. 3".

2.2 Electrostatic Model

The electrical field distribution in a typical cable construction is described by two-dimensional field models. The model is solved for a non-degraded system configuration as a base for further analysis. In addition, the cavity is introduced into the model cable insulation to investigate the effect of void presence on the XLPE electrical field insulation system. The mathematical field model for electrical field distribution in the cavity is created in respect of the single-phase XLPE cable "Fig.1" field model. The electric field intensity is obtained from the negative gradient scalar potential. The relationship equation of E and V is as follows:

$$E = -\nabla V \qquad (1)$$

The equation of the constitutive relationship between the electric field E and electric displacement D for the insulation material, in terms of the relative permittivity of the insulation and free space, are given in equation (2). The relationship between the electric field E and electric displacement D in the void or free space is given in equation (3):

$$D = \varepsilon E \qquad (2)$$

With: $\varepsilon = \varepsilon_0 \varepsilon_r$ where:

ε: is the relative permittivity.

ε_r : is the relative permittivity of insulation material.

ε_0: is the permittivity of free space.

D: is the electric displacement of the conductor which is directly proportional to the applied voltage to the conductor.

$$D = \varepsilon_0 E \qquad (3)$$

The forms of Gauss's law which is involves the free charge and the equation of electric displacement will be represented as:

$$\nabla . D = \rho \qquad (4)$$

where ρ is free charge density.

By substituting equation (2) and (4) in (1) and introducing the free charge as charge free density Poisson's scalar equation is obtained as:

$$-\nabla.(\varepsilon \nabla V) = -\nabla.(\varepsilon_0 \varepsilon_r \nabla V) = \rho \qquad (5)$$

Where ρ is the charge density.

Due to the application of cable material which has a constant permittivity ε applied, equation (5) becomes:

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \qquad (6)$$

If we admit that the charges density in the insulator is too weak and may be neglected, then equation (6) turns into Laplace's equation as:

$$\nabla^2 V = 0 \qquad (7)$$

The problem is solved regarding the solution of two-dimensional Laplace's equation:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \qquad (8)$$

Equation (8) will be used to calculate the electric field in the cable insulation and in the cavity by using finite element method in COMSOL multiphysics software in terms of boundary conditions.

1) **Boundary conditions:** The boundary condition "Fig.3" of the relationship of interfaces between two different medium for electrostatic model is mathematically express as [4]:

$$n.(D_1 - D_2) = \rho_s \qquad (9)$$

Where:

ρ_s: is the surface charge.

$n.D_1$ *and* $n.D_2$: are the normal components of electric displacement of any two different medium in the model.

Where the surface charges of the same insulation materials
in the model are neglected, the boundary condition is continuity and surface charge is zero as:

$$n.(D_1 - D_2) = 0 \qquad (10)$$

- The conditions of V and E are applied continuously.

The electric potential boundary condition:

- The conductor boundary condition: The sheath boundary potential is equal to 30 kV.
- The ground boundary condition: The sheath boundary potential is equal to 0 kV.

2.3 Implementation of the Finite-Elements Method

In order to predetermine the behaviour of an electrotechnical dispositive, it is necessary to know its geometry and its material's physical properties. The principal geometric parameters of the cable studied here are provided in "Table. 1".

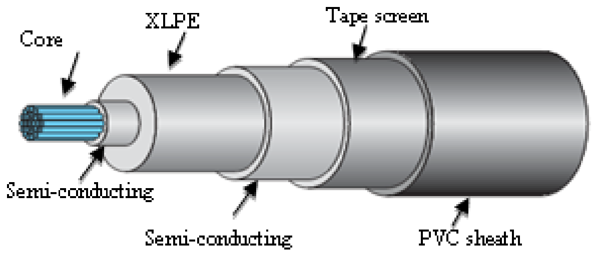

Figure 1. *Typical layout of single-core XLPE cable.*

After entering all the geometrical dimensions and physical properties of each sub-domain we obtained the cable in 2D show "Fig. 3". The cutting of the domain into finite elements is an essential step due to the dependence of the calculations on its precision; the mesh realised by 27204 triangular elements is represented "Fig. 4".

Table 1. *Geometrical parameters of the cable.*

Type	$185mm^2$,Al 30/50kV
1.Conductor radius	7.65 mm
2. Thickness of inner semi-conducting layer	1.00 mm
3. XLPE insulation thickness	11.3 mm
4.Thickness of outer semi-conducting layer	1.20 mm
5.Copper tape screen: wires and Cu foil	0.8mm, 25x0.1 mm
6.PVC sheath	5.3 mm
Dielectric losses factor (tg δ)	4.10^{-3}
Electric conductivity (σ)	10^{-12} $(\Omega.cm)^{-1}$
Thermal conductivity (k)	0.286 W/m.°C
Specific heat (C_V)	2.08 J/cm^3.°C

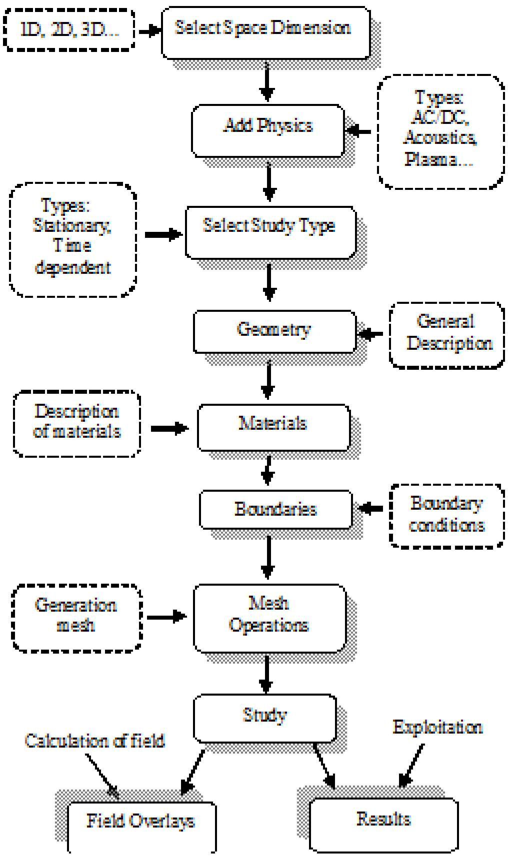

Figure 2. *Flowchart of the various stages of the FEM and software COMSOL.*

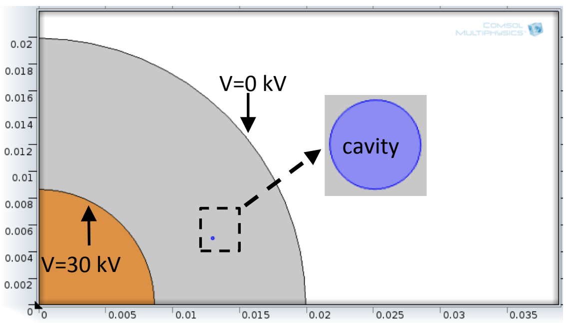

Figure 3. *Cross-section 2D of cable having a cavity with boundary conditions.*

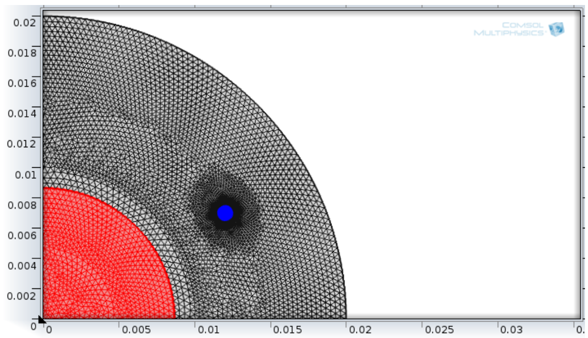

Figure 4. *COMSOL two-dimentional mesh model.*

3. Ignition conditions of partial discharges in the cavities

The field *Ec* of partial discharges starting in a cavity may be deduced from the Paschen's plot using the following approached expression [5]:

$$E_c = Kp^{0.7}d^{-0.3} \qquad (11)$$

Where:
$K = 8.10^{-0.3}$ for air.
p: the pressure inside the cavity.
d: cavity diameter.

The comparison of computed electric field values inside the cavities with regard to critical field values determined with equation (11) can be used to predict the partial discharges ignition.

4. Results and Analysis

Initially confirmed the validity of our fem model to calculate the distribution of the electric field in the absence of any defect, the results of fem and by analytical method are similar.
in order to verify the validity of the model in the case of a presence a cavity, we consider that the cavity the same insulating XLPE properties, as compared to the results obtained with homogeneous case are acceptable as in “fig. 5”.
After confirming the validity of the model and the completion of the study the case of homogeneity we turn to study the case of heterogeneity as follows:

4.1 Case of one cavity

We note that the presence of a cavity affects the distribution of the electric field in the region where it is located and this region is called influence region, which extends to many times the diameter of the cavity “Fig. 6”, the results show that the value of the field through walls less than a field inside the cavity. The study of change the distribution of the electric field by diameter

($d = 1\mu m\ to\ 20\mu m$) are shown in “Fig. 7”, where the size of the cavity does not affect the value of the field, in contrast to the position of the cavity where it whenever it was closer to the core was the most dangerous, the results of the change by the position compared to critical field are shown in “Fig.8”, we deduce that all cavities of diameter high than 1µm occurs partial discharges ($E \geq E_C$), such result confirmed by Kageyama [1].

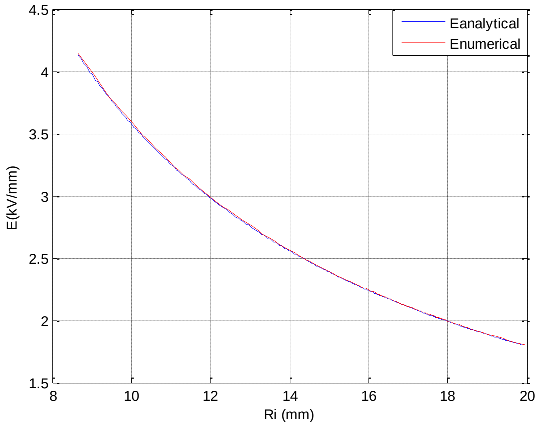

Figure 5. *Radial distribution of the electric field ($\varepsilon_a = \varepsilon_r = 2.3$).*

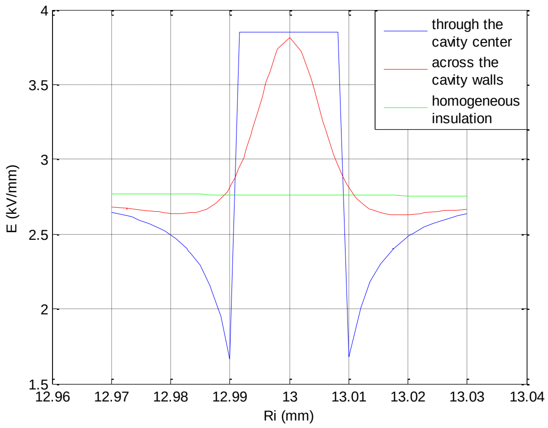

Figure 6. *Radial distribution of the electric field in the region containing cavity*

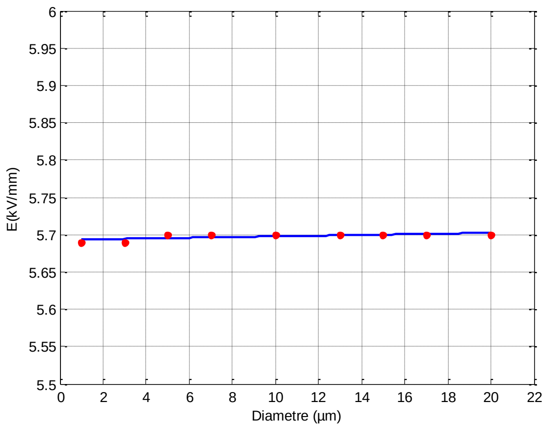

Figure 7. *Variation of electric field versus the cavity size.*

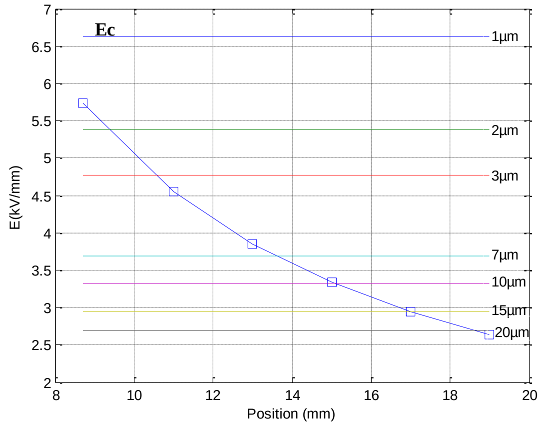

Figure 8. *Variation of electric field versus the cavity position.*

In "Fig. 9” we observe that the value of the electric field in the case of heterogeneity increase by about 40 % on the state of homogeneity, this increase is due to the difference in the electrical permittivity between the gas inside the cavity and permittivity of the insulator.

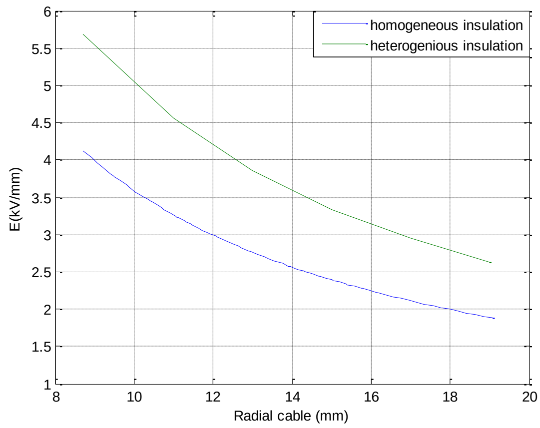

Figure 9. *Electric field distribution in presence and absence of a cavity.*

4.2 Case of two cavities

Initially we determine the effect of two cavities which have the same size and the same permittivity on the radial distribution of the electric field. After, we keep the same size of cavities and with different permittivities.

“Fig. 10” shows radial distribution of the electric field for the two cavities in interaction, the values of the electric field are of lesser values as compared to the case where one cell was alone in the same position and we note the field in the cavity located at the girdle side is high than the field in the cavity situated at the core side this is due the mutual influence between the cavities, and can be explained as follows: the cavity situated at the girdle side plays the role of a supplementary source of polarized the adjacent cavity [7]. Besides, the two fields inside and the walls of one cavity are identical, whereas they are different in the other one. The mutual effect of two cavities with different parmittivities is presented in “Fig.11”; the cavity situated outside contains water ($\varepsilon_r = 80$). The presence of water in the outside cavity leads to the important increase of the electrical field in the first cavity situated nearly to the core and reaches practically 5 kV/mm at the center and 4.2 kV/mm on the walls of the cavity. As the insulation degradation is in proportionality with the concentration of the cavities and their harmfulness, so the obtained result ascertains that the presence of water in the cable has a dangerous effect than the presence of air.

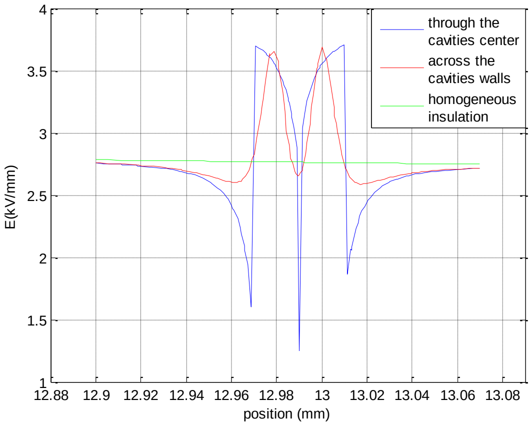

Figure 10. *Electric field distribution in two same cavities in interaction*

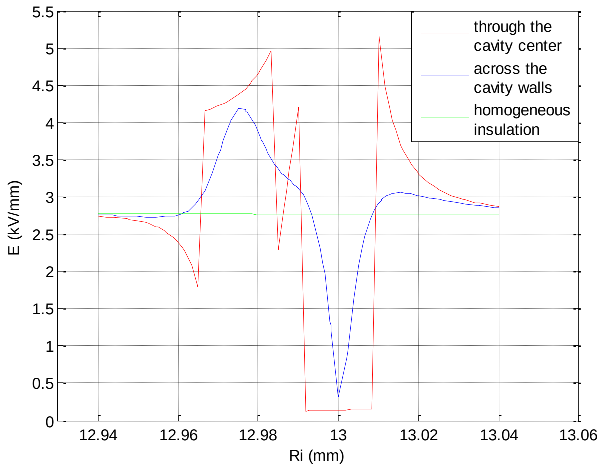

Figure 11. *Electric field distribution in two cavities different parmittivities.*

4.3 Case of a bi-cavity

We obtained the shape of a bi-cavity if the distance bitween the two cavities is less than the diametre of one cavity.

The results of computations shows that the size of the default practically does not affect the value of the field inside it. In constrat, the shape affects this this value. Indeed, for a given position, the field inside the special of the bi-cavity is 15 % higher than in the case of a unique cavity “Fig. 12”.

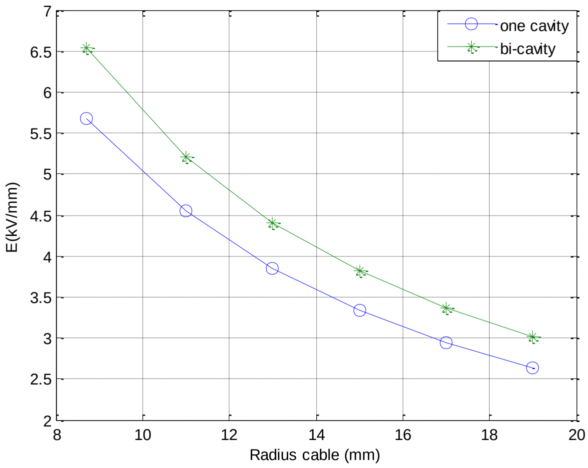

Figure 12*. Variation of the electric field inside the cavity with respect to its position, case of a unique cavity and a bi-cavity.*

5. Conclusion

From this study we can say that the electric field inside the cavity depends only of its position and shape. The partial discharges according to Paschen’s law initiated if $E \geq E_C$ and diameter of the cavity is higher than 1µm. As there is a mutual interaction between cavities is remarked.

In point of view the applied method, the Finite Element Numerical Method (FEM) presents a good tool to calculate the discontinuity of electrical field problem in high voltage cables.

Next time we will study the influence of mechanical constraints by FEM that come from the constraints of electric on the insulation of cables.

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