





IMPACT OF HETEROGENEOUS CAVITIES ON THE ELECTRICAL CONSTRAINTS IN THE INSULATION OF HIGH-VOLTAGE CABLES

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Abstract

The main insulation layer is the most important layer of the high-voltage cable, and the quality of this material directly affects the life of the cable. It is also known that contamination, porosity and associated partial discharges in the insulation can affect the service life of cables. In this paper, we use the COMSOL Multiphysics software, which is based on the finite element method in AC/DC, 2D electrostatic. Our study shows the effect of heterogeneous cavities on the functioning of electrical cables. This work contains the study of electric field distribution and potential of a model of high voltage cable; we took into account the absence and the presence of heterogeneous cavities. The study was conducted using numerical results with mathematical validation. The obtained results are considered satisfactory, favorable and very promising.

Key words: Cables, defect, electric field, electric potential, heterogeneous cavities.

1. INTRODUCTION

Transmission lines are a vital link in the power transmission electric grid, either underground lines or overhead lines [1-8].

The reliability of electrical systems depends, among other things, on the quality of the electrical insulation systems (EIS). Many constraints, electrical, mechanical, chemical, thermal, environmental and mode of operation, can lead to aging and lead to the partial or total loss of the insulation function [5].

Underground cables are expensive electrical equipment that should be used for as long as possible. These cables contain a dielectric made of polyethylene hardened (PRC) or polyethylene cross-cutting (XLPE).

The vast majority of power outages are caused by failures in ground cables. The origins of these defects differed and can be divided into four categories:

- external effects: mechanical damage, etc., are many external attacks that are supposed to resist protective layers of cable,
- production defects We frequently note the inclusion of cavities and impurities in insulating

cables during their production (the goal of our thesis),

- incorrect application or incorrect installation,
- statute of limitations of insulation [6-8].

However, the numerical approach allows more advanced and more reliable applications and less costly and scalable specific developments [9].

In this context, Uydur et al.[10] describes how to perform electric and magnetic field analysis on XLPE insulated power cables. Electric field analysis of $1 \times 240/25 \text{ mm}^2$ was performed using different shapes of equal area. As a result, cables, cable terminations and cable connections can be further compressed and lead to insulation failure. Florkowski,[11] Florkowski, describes the influence of insulating material properties on DC partial discharge. The author is demonstrated the partial discharge mechanism and draw attention to the role of the parameters of the insulating material next to the cavity in the dc voltage. These investigations were carried out on two dielectric materials used in power cables. The main observation relates to the effect of the cavity resistance of adjacent materials on the DC partial discharge initiation voltage threshold. Medoukali et al. [1] calculate the electric field and they determine the electrostatic pressure for various space-charge density values. The

elongation of micro-cavities is calculated for appreciating the effect of the electrostatic pressure on the walls of the cavity. Boudjella et al. [12] A numerical simulation of the magnetic field of a 400 kV underground power line used as a prototype of a new type over short distances in several countries is presented in two dimensions using Comsol Multiphysics and Matlab software. The simulation results illustrate the variation of the magnetic flux density in terms of amplitude and distribution as a function of different actual harmonic rates. Khouildi et al [13] analyze the influence of heterogeneous cavities and the influence of their positions and sizes on the electric field distribution, the potential distribution and the degradation of the cross linked polyethylene XLPE insulation. Elaggoune et al. [14], evaluated the health of electrical cable terminations using the dissolved gas analysis which is an effective chemical method to guarantee a detection of partial discharges in cable terminations. To remedy with this problem, Radial Basic Functions neural network is applied as simulation tool. The results obtained allowed to conclude on the effectiveness of the RBF neural network in the field of diagnosis and monitoring of terminations against the phenomenon of partial discharges. Seghier et al. [15] treated the combined effect of space charge and cavities on field, potential and temperature distribution within solid insulation cross-linked polyethylene (XLPE) used in the electrical insulation of underground high voltage power transmission cables. The conclusion that the cavities constitute a critical situation if they are located close to the high voltage electrode. On the other hand, this quantity is independent of the size. Seghier et al. [5] evaluated the partial discharges phenomenon (PDs) by simulation, experiment and mathematical validation which occur in a solid insulator containing defects. These defects, if they did not exist during the operation of the implementation. The results show that the electric field in a cavity depends on its position in the insulating part.

In fact, we tried to show the influence of several factors on the appearance and activity of PDs. Using the Comsol Multiphysics software, we dealt with the effect of size, shape, location and orientation and the electric field of the defect on the DPs.

The aim of the present study is to consider the phenomenon of partial discharges in solid insulators. We try, more particularly, to highlight the various factors which can influence and support the appearance of this harmful phenomenon, like the existence of defect of various sizes and form and the existence of space charge in the volume of insulation.

To approach this study, and to locate the problem of the influence of the characteristics of a cavity on the phenomenon of the partial discharges, we will determine the influence of the cavity itself on the distribution of the electric stresses. A cavity is characterized by its size, its geometric shape, its position (the choice of the position is made in a

random way), its orientation with respect to the field lines as well as its presence or not with other cavities.

At the end we will try to qualify the appearance of partial discharges according to these characteristics.

The objectives of this work are, on the one hand, to contribute to the study the impact of the presence of the cavity on the electrical constraints in the insulation of high-voltage cables by simulation by simulation and a mathematical model becomes literature [5].

The present work allows us to study the electric potential and the distribution of the electric field by means of the comsol software based on the finite element method.

The rest of this paper is arranged as follows: section 2 briefly describes the structure of the cable used in this study. Section 3, shows the design of computational approach using comsol multiphysics. Then, the results are presented in section 4. In the last,(section 5) we present the results of different simulations (with and without defects) performed on the cable, investigating the effect of the heterogeneous cavity position on the electric potential and electric field by mathematical verification, then section 7 concludes this paper.

2. STRUCTURE OF CABLE

An electric cable is a set of conductors that allows the circulation of an alternating or direct current, from the generator to the device to be powered.

The cable consists of: (see figure 1)

- several single-strand or multi-strand cores (also called conducting wires) in copper or aluminum,
- an insulating sheath for each conductor which prevents short circuits,
- and finally a mechanical protection envelope [9].

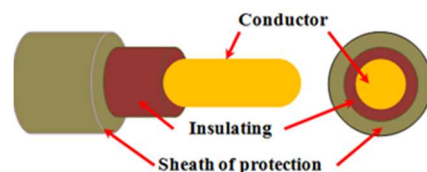


Fig. 1. Cable structure

The structure of a high voltage cable has a favorable effect on its performance. Structural and manufacturing techniques for XLPE cables have greatly improved since the first production cables, which had wide-ranging problems. High voltage cables consist of the low voltage cables of three main conductive parts, insulation and protective sheath. But at the difference of low voltage cables, an additional layer is added so that the electric field is homogeneous around the conductor. The conducting core is composed of more conductors usually copper or aluminum. Around this set of conductors is a semiconductor material (SC) intended to

homogenize the electric field at the interface between the semiconductor and the insulation. Then, there is the essential part which is the insulating material.

Usually, high voltage cables are manufactured by co-extruding all three SC/PRC/SC layers under high pressure, in order to obtain a material as homogeneous as possible and especially without cavities [6-7].

3. CALCULATION METHOD

COMSOL Multiphysics is a computer program that uses finite element methods to solve partial differential equations (PDEs) that define the problem under study. In order to prepare a complete simulation, many steps must be followed. A simple schematic of these steps is shown in Figure 2.

Step 1. Create geometry (physical model). An isolator element (chain of isolator elements) is defined using an interface. Inputs to this interface are the x and y coordinates of all points that define the geometry of the cable.

Step 2. Record the various parameters of the geometric physics interface. In fact, the material properties (insulation, conductors, heterogeneous cavities and air) are defined. These properties include the permittivity and conductivity of each material. In addition, boundary conditions and applied voltages (HV and 0V) are performed.

Step 3. Creation of the mesh grid. A user-controlled mesh is built automatically. Indeed, the element size parameters and free quad settings are applied.

Step 4. A default solver sequence is defined for a stationary analysis to compute the distribution of the field and electrical potential.

To simplify electric field calculations that satisfy these conditions, COMSOL uses the potential (V) derivative defined by the following field-potential relationship: [16-17]

$$\vec{E} = -\text{grad } V \tag{1}$$

Obtaining Poisson's equation is exceedingly simple, for from the point form of Gauss's law:

$$\nabla \cdot D = \rho \tag{2}$$

The definition of D:

$$D = \epsilon E \tag{3}$$

and the gradient relation, (equation 1) or:

$$E = \nabla V \tag{4}$$

By substitution equ.2, 3 and 4, we have:

$$\nabla \cdot D = \rho = \nabla \cdot (\epsilon E) = -\nabla \cdot (\epsilon \nabla V) = \rho \tag{5}$$

or:

$$\epsilon \nabla \cdot (\nabla V) = -\rho \tag{6}$$

without charge $\rho = 0$, Poisson's equation becomes Laplace's equation:

$$\epsilon \nabla \cdot (\nabla V) = 0 \tag{7}$$

finally:

$$\nabla^2 V = 0 \tag{8}$$

Solve the potential V equation on a user-programmed field and define source and boundary conditions. In this case, we use the model we studied to use an underground cable consisting of three parts with different properties: the insulation having a relative permittivity equal to $\epsilon_r=3$ and the conductivity $\sigma=10^{-14}$, the conductive core the copper electrodes of relative permittivity of $\epsilon_r=10^6$ and conductivity of $\sigma=10^6$, heterogeneous cavities with relative permittivity of $\epsilon_r=1$ and conductivity of $\sigma=10^{-12}$. The air around the insulator model has a permittivity of $\epsilon_r=1.0005$ and $\sigma=10^{-14}$.

4. SIMULATION RESULTS

The numerical simulation of Comsol Multiphysics consists of a family of solvers for balance equations (linear, non-linear, stationary...etc). (figure 2).

A very good modeling of the characteristics of the power lines depends on several parameters such as: the characteristics of the power cables (conductivity, shape of the wire, cross section, etc.), see figure 1. Cable insulation is high density polyethylene used from our work. The physical characteristics of the cable chosen according to the bibliographical reference [5,6-7], are presented in the following table 1.

Table 1. Physical characteristics of the cable used.

Rms value of nominal voltage (V_n)	12kV
Conductor radius (r)	3mm
Thickness of the insulating envelope (R)	7mm
PVC protective sheath thickness	2.5 mm
Electric conductivity	$10^{-12} \Omega \text{ cm}^{-1}$
Heat conductivity	0.286 W/(m.°K)
Specific heat	2.08 J/(cm3.°K)

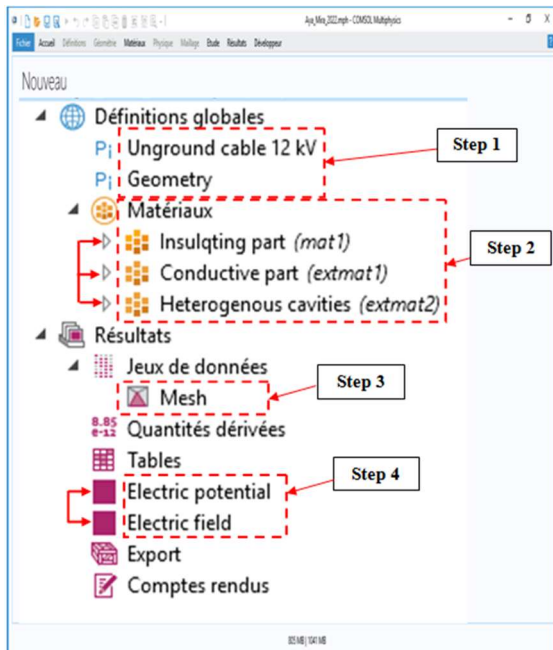


Fig. 2. Structure that determines the main steps to create a COMSOL model

The first thing to do once the program is open is to draw the geometry of our system (cable). This cable is made up of several layers, for example, insulating layer and PVC protection, etc. With simplifying hypotheses, Comsol multiphysics use the finite element method, the principle of which is described in figure 2.

Cable modeling and simulation can be summarized in the following six successive steps:

- The first step consists in defining the geometry of our system (cable) in two dimensions, according to table 1, with or without the presence of a cavity with of heterogeneous cavities and of the order of μm in the volume of the field of study and in the desired position, sees figure 3.
- second step involves defining the electrical properties of the material present. This includes defining the relative permittivity and conductivity of each section (conductive sections have insulating sections) (Figure 3).
- The third step defines the boundary conditions which result in the potential imposed on each electrode, for the electrode activates a constant potential of value 12 kV and the ground electrode 0V, (Dirichlet conditions),
- The fourth step, dealing with the density of finite elements (mesh) is important for critical regions where greater precision is required, because the electrical properties of materials are very changeable. Indeed, we considered:
 - Without defect Triangular mesh consists of 1118 elements, with solution time 0.142 s.
 - With defect (Presence of a heterogeneous cavity) Triangular mesh consists of 1922 elements, with solution time 0.231 s.
 - With defect (with three heterogeneous cavities) Triangular mesh consists of 3542 elements, with solution time 0.366 s.

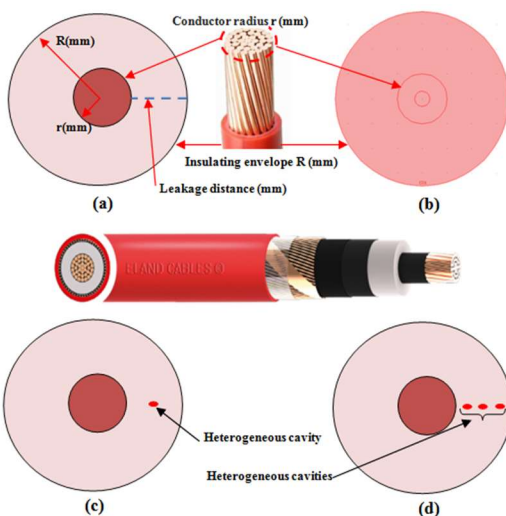


Fig. 3. Different configurations of the cable used in our work: (a) Without defect, (b) Without defect in Comsol Multiphysics software, (b) With defects (presence of a heterogeneous cavity), (c) With defects, three heterogeneous cavities (elliptical shape defect)

For all the cases studied are mentioned in the figure 4.

- The fifth step is dedicated to the resolution of the problem by the application of the numerical method and by the construction of the system of equations (eq.8), and this by introducing the factors of each part of the equation.
- The sixth and last step consists of displaying the results, such as the distribution of electric potential and field, which will then be taken to Matlab to draw the necessary curves.
- Our work will be validated through a mathematical model which was presented in the reference [5].

- Electric potential :

$$V(r_i) = \frac{V_n}{\ln(\frac{R}{r})} \ln(\frac{R}{r}) \quad (9)$$

- Electric field :

$$E(r_i) = \frac{V_n}{r_i \ln(\frac{R}{r})} \quad (10)$$

Such as:

V_n : The nominal cable voltage (kV),

R : Radius of the insulating envelope (mm),

r : Radius of the conductor (mm),

r_i : step (mm).

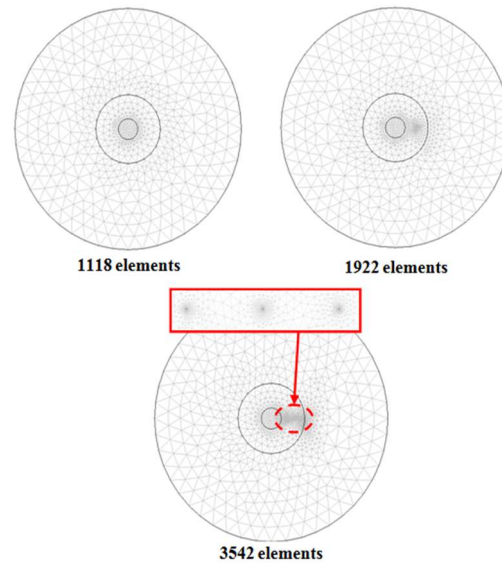


Fig. 4. Discretization by finite elements Mesh of the cable (Triangular mesh)

5. RESULTS AND DISCUSSION

This part is devoted to the study of the distributions of the electric potential and field for an underground electric cable high voltage (HV). We plot the potential and the field as a function of the leakage distance r (mm) shown in figure 3, to see the impact of one or more heterogeneous cavities (presence of a manufacturing defect in the electrical cable).

5.1. Distribution of electrical potential

We present in what follows, figures 5,6 et 7 the distribution of the electric potential in two cases:

with and without defects, (Presence of a heterogeneous cavity, with three heterogeneous cavities (elliptical shape defect).

Figure 5, this is the case where the insulation in two cases: contain defects and does not contain any defects. We find that the voltage at the active electrode part is fixed (cable core) 12kV.

Figure 5 (a), presented the case where the insulation does not contain any defects, and figure 5

(b et c), where the insulation contain a defects (heterogeneous cavities), these results we can conclude that the voltage distribution is uniform and that the area close to the HV electrode is the most constrained while that near the earth electrode the voltage is almost nothing. No remarkable difference is observed.

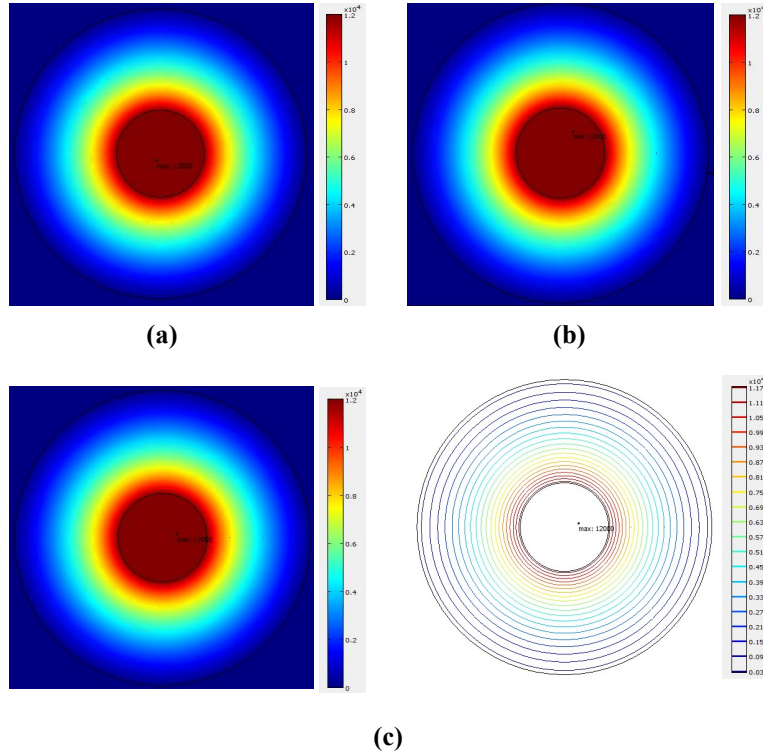


Fig. 5. Distribution of electric potential $V=12$ kV: (a) without defect, (b) with defects (presence of a heterogeneous cavity), (c) with defects, (with three heterogeneous cavities)

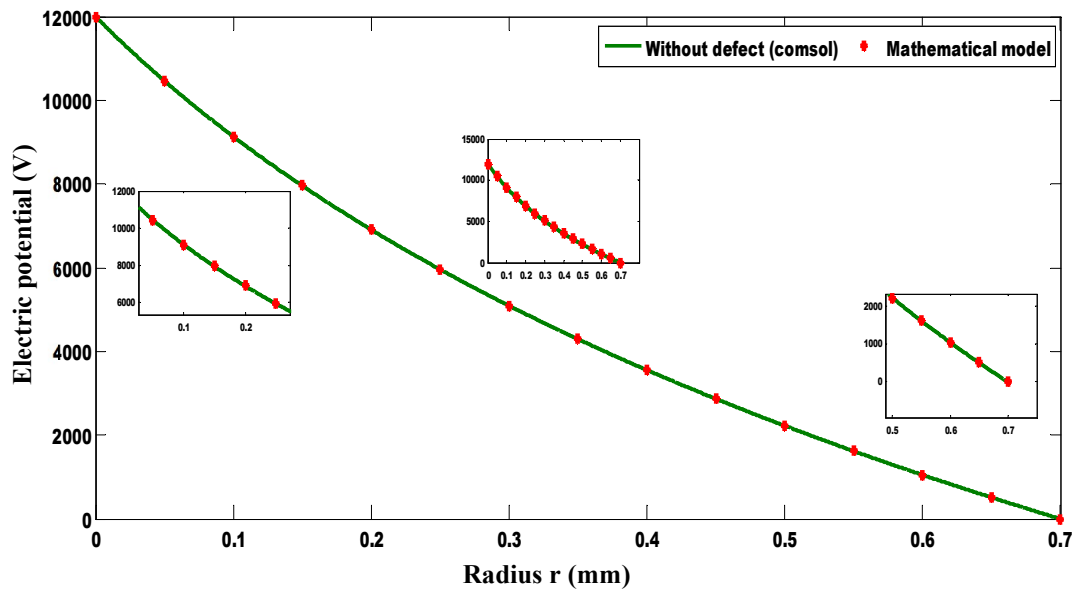


Fig. 6. Radial distribution of the electric potential in the without defect. (Mathematical & numerical model)

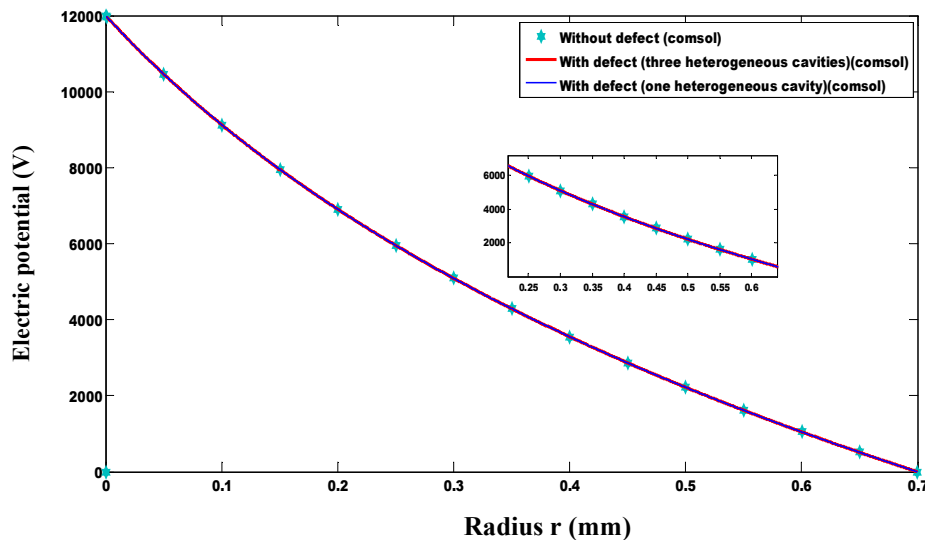


Fig. 7. Radial distribution of electric potential with and without defects, (a) :the presence of a cavity, (b): one heterogeneous cavity, (c): three heterogeneous cavities

According to the figure 6, the calculation result by the Comsol software shows that, in the insulating part, starting from the end of the active electrode, and in accordance with the mathematical model, the electric potential decreases according to a logarithmic function. The calculation results coincide with those of the mathematical or analytical model.

By comparing the results relating to the potentials obtained when the cable is clean (without fault) and when it is with defects presented in figure 7, we observe no modification of the distribution of the potential, mainly due to the presence of one or more cavities inside the insulation.

So, the maximum value of the electric field in a defect is independent of the size of the defect, it can be concluded that partial discharges are more favored in the case of large dimensions.

5.2. Electric field distribution

An electric cable is a set of several wires running side by side or bundled together, which is used to carry an electric current. They must be able to transfer electrical energy.

High voltage cables are made up of three main parts like low voltage cables: conductor, insulation and protective sheath.

But unlike low-voltage cables, an additional layer is added so that the electric field is homogeneous around the conductor.

In what follows, we present in the following, the radial and distribution of the electric field in two cases: without and with defects, (one heterogeneous cavity, and three heterogeneous cavities). See figures 8, 9 and 10.

For figure 8, presented the electric field distribution in two cases studied. Without and with defects, (with presence of heterogeneous cavities).

The electric field is practically zero inside the active electrode, because the electrode is conductive. We clearly see that the electric field is concentrated

only on the element subjected to a voltage (electrode HV).

Figure 9 gives the radial distribution of the electric field along the insulating part, in the case with fault, five cases are studied. It is clearly shows the radial distribution of the field along the insulating part. It shows a uniform decrease. The numerical solution coincides with the mathematical model.

However, figure 10 gives the radial distribution of the electric field along the insulating part, in the case with defect, two cases are studied. The impact of the presence of presence of heterogeneous cavities, (elliptical shape defect) of the order of a micrometer in diameter, in the region where it is located. We can clearly see the field distortion inside the defect.

The electric fields lines diverge from the active electrode (directed from the HV electrode towards the cable ends and converge towards the ground electrode). The distribution of the field lines is non-uniform, so the system becomes as a point-plane configuration.

A quantitative comparison of the electric field, in the case with and without defect is shown in figure 10 it shows well an increase in the value of the electric field in a fault which is located just in the middle of the insulation. This increase in the value of the field obviously explained by the low value of permittivity of the air. Indeed shows that this increase is greater when it is located near the active electrode.

6. CONCLUSION

This article represents a contribution to the study of the impact of heterogeneous cavities on the electrical constraints in the insulation of insulated HV high voltage cables by analyzing the distributions of the electrical field and potential on an underground cable of 12 kV high voltages.

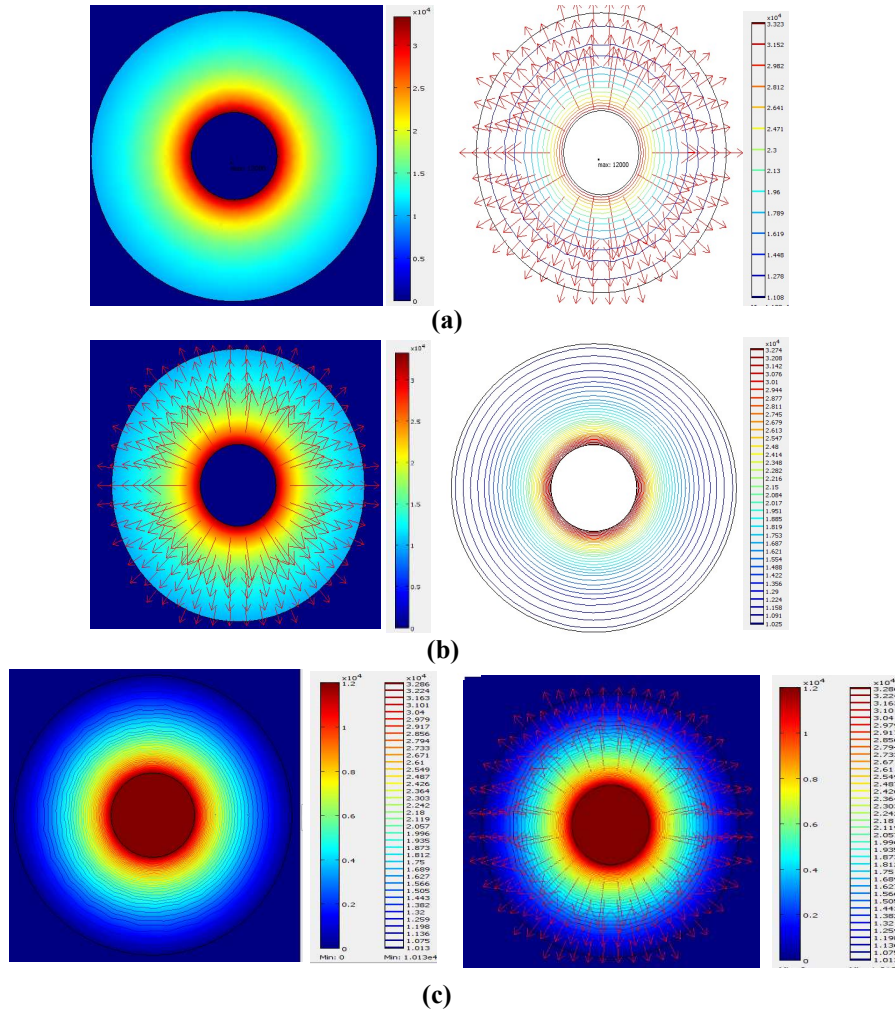


Fig. 8. Radial distribution of electric potential with and without defects, (a): the presence of a cavity, (b): one heterogeneous cavity, (c): three heterogeneous cavities

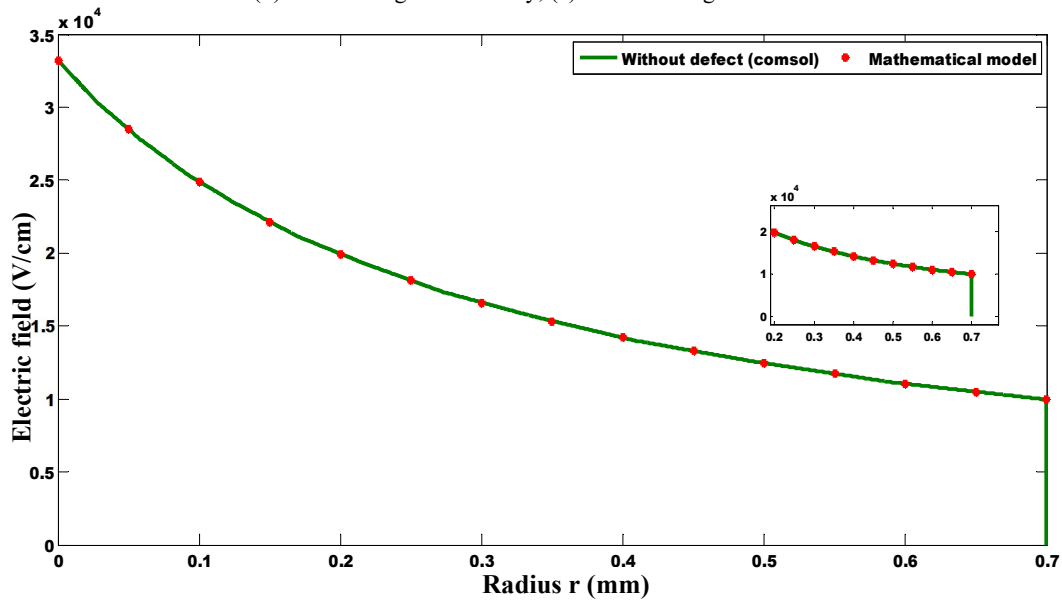


Fig. 9. Radial distribution of the electric field in the without defect. (Mathematical & numerical model)

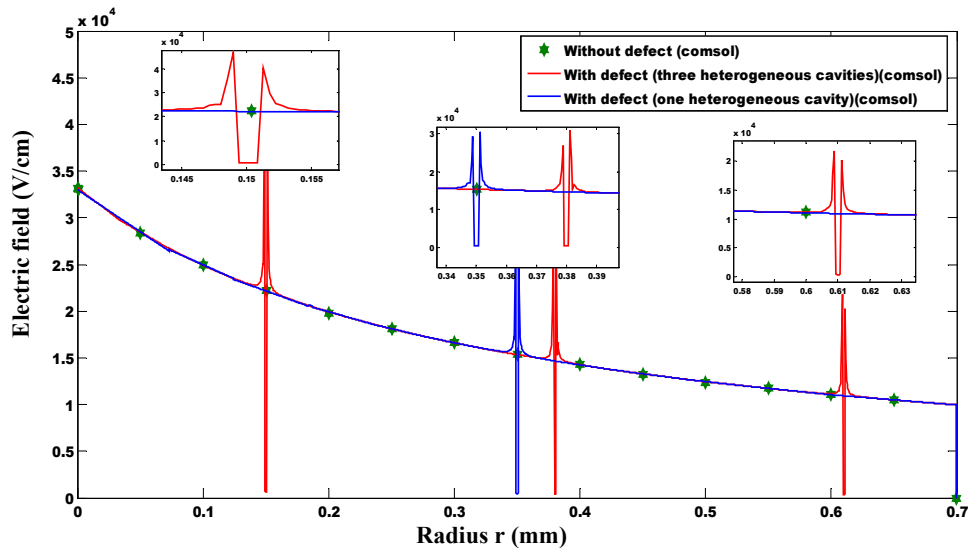


Fig. 10. Radial distribution of electric field with and without defects, (a): the presence of a cavity, (b): one heterogeneous cavity, (c): three heterogeneous cavities

The study was conducted using the Comsol Multiphysics software based on the finite element method with mathematical validation.

This work allowed us to conclude that:

- Firstly, we have proven that the commercial software Comsol Multiphysics are one of the best numerical methods to simulate the behavior of an underground cable under AC voltage.
- The presence of faults (defects) in an underground cable influences the distribution of the electric field in the region where it is located.
- a large dimension defect is more dangerous and the system becomes less rigid. (Partial discharge occurs at lower voltage levels)
- The results show that the position of the cavity has a considerable influence on the electric field.
- It leads to the conclusion that the cavities constitute a critical situation if they are located close to the nucleus. The electric field is stronger and can reach the field of air breakdown.
- The positions of the cavity greatly influence the electric field. As the cavity approaches the active electrode, the electric field increases. These defects result from harmful consequences on the state of health of the cable and from internal discharge problems, so excessive heating will cause material degradation and premature aging. In terms of perspective, we hope that this work will be developed by examining the effect of mechanical stresses and electrical stresses on cable insulation by means of the finite element method. This aims to present the different factors from the point of view of modeling and numerical simulation of the physical phenomena that occur on the cable, in particular temperature, humidity and pressure, which are closely related, as seen by others comparing numerical tools for the study.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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