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SIMULATION OF THE POTENTIAL AND ELECTRIC FIELD DISTRIBUTION ON HIGH VOLTAGE INSULATOR USING THE FINITE ELEMENT METHOD

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Abstract

The knowledge of the distribution of the electric field within and around high voltage equipment is a crucial aspect of the design, exploitation and performance of high voltage insulators. It could be useful for the detection of defects in insulators. The objective of this study is predicting the behavior of polluted insulator under AC voltage. For thus, the distribution of the potential and the electric field along high voltage insulator is investigated using a numerical method. The commercial Comsol Multiphysics proved to be one of the best software used in 2D modeling. The potential and the electric field distributions along this insulator are simulated under various conditions: the two cases: clean and polluted insulators and applying different conductivity values. We used electrostatic 2D simulations in the AC/DC module. The results are auspicious and promising.

Keywords: Simulation, MEF, high voltage, electrical potential, electric field.

1. INTRODUCTION

The importance of research on insulator pollution has increased considerably with the increase in transmission line voltage [1-2]. Indeed, The performance of insulators in a polluted environment is one of the guiding factors in the insulation coordination of high voltage transmission lines [3]. Transmission lines and high voltage transformer used in electric power delivery are subject to various constraints such as insulator pollutions, which is of prime interest regarding power quality issues and reliability [4].

Flashover pollution caused by the insulators used in high voltage transmission is one of the most significant problems for power transmission. It is a problem due to several reasons like difficulties in modeling the complex shape (form) of the insulator, different pollution density at different regions, non-homogenous distribution on the pollution area of the insulator, and the unknown effect of humidity on the pollution [5-6]. Cap and pin insulators are widely used in power transmission and distribution lines for a long time. Electrical insulators frame an essential segment of high voltage electrical systems, such as sub-stations and transmission and distribution lines which are used to support the line conductors to free them electrically from each other [7]. Insulator pollution phenomena are considered as a continuous or intermittent accumulation (deposition) of impurities coming from various sources. It can result from a cloud of smokes (industrial and urban pollution) [8], or small particles of salt in coastal regions (marine pollution)[9-10], even fine particles are coming from a sandstorm in the desert regions (desert pollution) [11-14].

Recently, the numerical models based on the finite element method [15-16] give better results in the modeling of the flashover phenomenon of the insulators polluted compared to the static and dynamic models. Consequently, it is essential to model the electric fields and potentials to analysis the characteristics and the behavior of the polluted insulators. The electric field and potential distribution can be estimated using various numerical techniques, such as Charge Simulation Method (CSM), Finite Difference Method (FDM), Boundary Element Method (BEM) and Finite Element Method (FEM). In the field of high voltage transmission line applications, the published results of the numerical simulation of the potential distribution and the electric field of some studies are all for simple geometries [17-22]. A numerical simulation is an approach that gives researchers the possibility to analyze the behavior of several phenomena which, because of their complexity, are beyond the scope of classical calculus [16]. For this reason, COMSOL Multiphysics can serve as a powerful and interactive way to solve complex problems using the finite element method. COMSOL Multiphysics is a widely used tool in various fields of scientific research. It amply facilitates the modeling steps.

The Finite Element Method (FEM) is most well-situated to calculate the electric field and potential distribution in high voltage insulator because it is one of the more successful numerical methods to solve electrostatic problems (using the discretization of the domain)[23]. Hence, it is a flexible method and leads to relatively simple techniques allowing to estima te the fields at the surface of the electrode thin and highly curved with various dielectric materials, which is well adapted to problems of complicated geometry [24-27].

In this article, the two dimensions of finite element method (FEM) developed by real geometrical dimension, and it is implemented to calculate the electric field and the potential distribution of the insulator. The primary objective is to study the electrical field and potential distribution of clean and dry insulator under discontinuous uniformly polluted. Electric field and potential distribution along a cap and pin insulator (1512L) was calculated in COMSOL Multiphysics. Electric currents formulation was used to study the effect of pollution conductivity on the electric field distribution. The thickness of pollution layer was fixed (L1: Level of discontinuous pollution). Various conductivities employed to investigate the effect of pollution on electric field and potential distribution.

The study described below was carried out by the COMSOL Multiphysics software. This article is organized as a development of the FEM model, solving the FEM(discretization), the discussion of the results of electric field and potential distribution which considers the real shape of an insulator and adds different conductivities and applied voltage of the line has been computed. The rest of the paper is organized as follows. Section 2, provides a brief description of the real model of insulator, parameters and material properties in the Finite Element Method (FEM). In Section 3, finite element methods of analysis to estimate the electric field and potential distribution is presented. By section 4, we give and we discuss the different results obtained by using Comsol Multiphysics simulation. Finally, conclusions of the present work are drawn.

2. METHOD OF THE SIMULATION

COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs). With this software, we can easily extend conventional models for one type of physics model into multiphysics models that solve coupled physics phenomena. It is possible to build models by defining the physical quantities, such as material properties, loads, constraints, rather than by defining the underlying equations. You can always apply these variables, expressions, or numbers directly to solid domains, boundaries, edges, and points independently of the computational mesh. In our work, each material (glass, portland, air, and cement) (fig. 2 (a)) define by its permittivity and conductivity, (table 2) and we pass to the boundary conditions. COMSOL then internally compiles a set of PDEs representing the entire model. You access the power of COMSOL through a flexible graphical user interface, or by script programming in the COMSOL Script language.

Cap and pin insulators have four major components. They consist of an insulating block carrying to its upper part a cap sealed out of malleable pig iron and inside a steel stem, with grooves and whose conical head is also sealed in glass. The lower end of this stem is round and has dimensions wanted to penetrate in the cap of the following element and to be maintained by a pin there.

In this part, an insulator made of the glass material is considered for the simulation dimensions of the 220 kV insulation. Figure and table 1 give the real parameters of the insulator used in the simulation. The FEM model of the real insulator is depicted in figure 2.

We examine the electric field and potential distribution of glass insulator in two different surface conditions. The first, in the clean model and the second, under discontinuous pollution for different conductivities. The properties of the materials of the various domains of the insulator (cap, pin, glass..etc.) are shown in table 2.

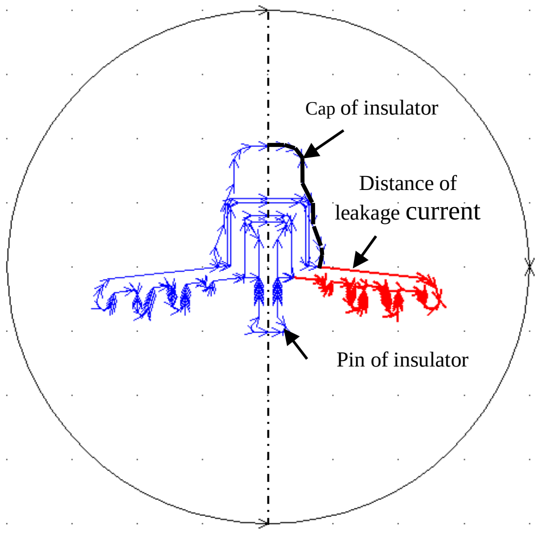


Fig. 1. Parameters of cap and pin insulator 1512L

Table 1. Geometrical parameter of cap and pin 1512L insulator

Parameters	Size (mm)
Distance of leakage current	292
Cap of insulator	244
Pin of insulator	125

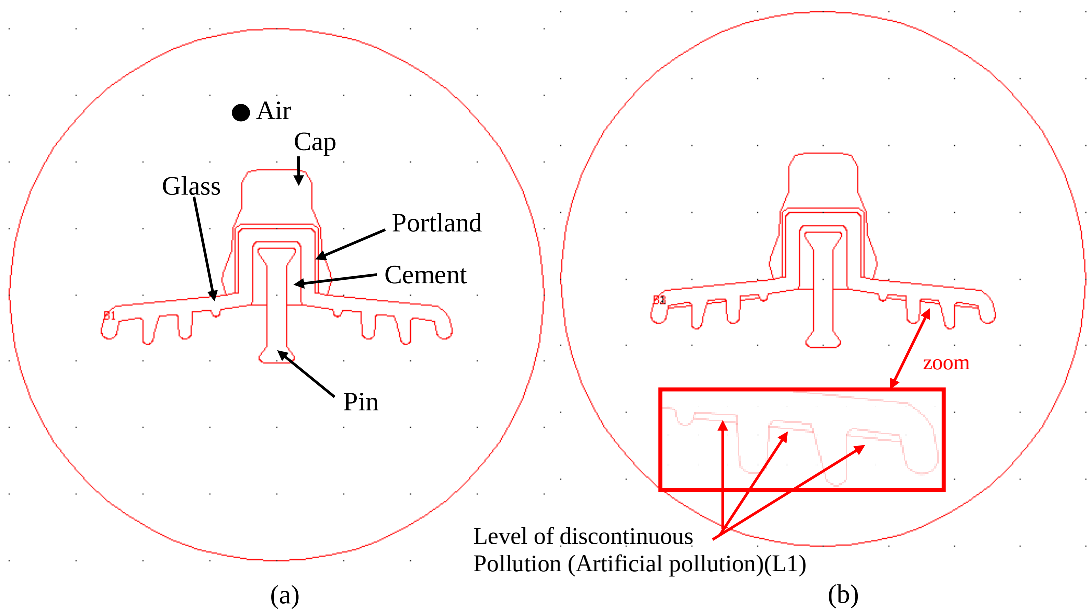


Fig. 2. FEM model in the software of 220kV insulator
(a) Clean model, (b) Discontinuous uniformly polluted model

Table 2. Material properties of FEM model of cap and pin 1512L insulator

Properties	Cap & pin	Glass	Portland & Cement	Air	Artificial pollution
Relative permittivity (ε_r)	10^6	6	5	1.0005	80
Conductivities $(\mu s/cm)$	10^6	1.e^{-12}	1.e^{-12}	1.e^{-14}	0,70,700, 1200,3000

3. MATHEMATICAL MODEL

Electrostatic problems consider the behavior of electric field intensity: E, and electric flux density (alternatively electric displacement) : D. There are two conditions that these quantities must obey. The first condition is the differential form of Gauss Law, which says that the flux out of any closed volume is equal to the charge contained within the volume [28-29]. The basic equations used to calculate the potential (electric field) are Maxwell's equations:

For the electrostatic model, the following equations are used:

$$div\,\vec{D} = \rho \quad (1)$$

$$\vec{D} = \varepsilon \vec{E} \quad (2)$$

$$\vec{E} = -\overrightarrow{grad}\,V \quad (3)$$

The combination of these three equations gives:

$$div\,\varepsilon(-\overrightarrow{grad}\,V) = \rho \quad (4)$$

$$div\,\varepsilon\,\overrightarrow{grad}\,V = \rho \quad (5)$$

This expression (4,5) is called the Poisson equation. So the Laplace's equation can be obtained by making space charge $\rho = 0$.

In our case, in high-voltage equipment, space charges are not present or negligible $(\rho = 0)$ and therefore the equation to be solved for the dielectric media is [30-31]:

$$div\,\varepsilon(-\overrightarrow{grad}\,V) = 0 \quad (6)$$

The program solves (6) for voltage (potential) distribution V over a user-defined domain with user-defined sources and boundary conditions.
For conductive media in stationary mode, it comes, since $div\,\vec{j} = 0$ et $\vec{j} = \sigma\vec{E}$:

$$div(\sigma(-\overrightarrow{grad}\,V)) = 0 \quad (7)$$

The equation of the place in Cartesian coordinates is:

$$div\,\overrightarrow{grad} = \frac{\partial^2 V}{\partial^2 x} + \frac{\partial^2 V}{\partial^2 y} + \frac{\partial^2 V}{\partial^2 z} \quad (8)$$

The calculation software determines the electrical potential to obtain the field distribution by solving the following partial differential equation for two dimensions [20].

$$-div\,\varepsilon\,\overrightarrow{grad}\,V - div\,\sigma\,\overrightarrow{grad}\,V = 0 \qquad (9)$$

For resolution steps in Comsol Multiphysics can be summarized in the following four successive steps:

- The first step is to introduce the two-dimensional (2D) geometry of the 1512L insulator to the Comsol (software).
- The second step concerns the definition of the electrical properties of the materials used. It consists of defining the relative permittivities ε and the conductivities σ for each part of the insulator. Also, it is necessary to define the boundary conditions which are translated into the potential imposed on each electrode (Dirichlet conditions).
- The third step is devoted to solving the problem by applying the numerical method and the construction of the system of equations ($-div\,\varepsilon\,\overrightarrow{grad}\,V - div\,\sigma\,\overrightarrow{grad}\,V = 0$), and this by introducing the factors of each part of the equation.
- The final step is to solve the problem and display the simulation results as the potential and electric field distribution.

The algorithm simulation computer flowchart for COMSOL is illustrated by figure 3.

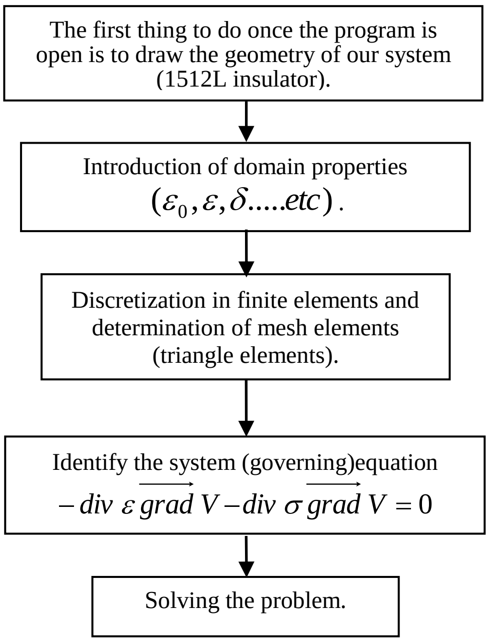


Fig. 3. Resolution Steps by COMSOL Multiphysics

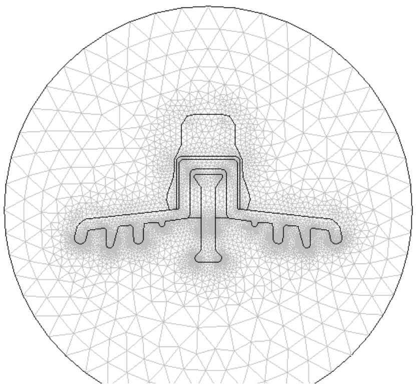
4. RESULTS AND DISCUSSION

Electric field distribution and voltage distribution mainly depends on applied voltage, properties of materials used in insulator and surrounding or environmental condition.

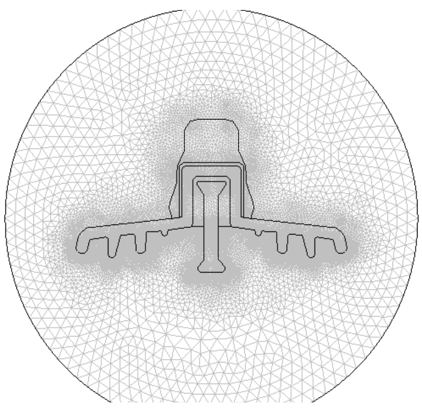
Pollution effect plays an important role in determining the potential distribution and the electric field along the insulator. To demostrate this effect, several values of the conductivities of the pollution layer were used. The clean case was also introduced for reference, we suppose that the Finite Elements Method was best suited to the constraints imposed by the problem. Also, this method has been successfully applied in calculating the electrical field and potential distribution around the insulators. We introduced presented our model with all its specifications in table 2 to this software. Due to the complexity of our real model, we have drawn the model in the FEMM software; then we call the model in the software comsol, we followed all the steps as shown by figure 3. We fixed the applied voltage of the active electrode with 30 kV

The density of the mesh is higher in the critical areas (regions) of the insulator, where higher precision is necessary. The mesh of the studied field in 2D was refined at the insulator, metallic pieces to get a better precision, the conductivities used for this study are chosen according to the study carried by [1].

Numerical results for different meshing presented by figure 4. In fact, the type of the mesh has been changed based on the elements number. For thus, two meshes have been tested. The first case corresponds to a coarse mesh composed of 15668 elements (see figure 4(a)). The second case corresponds to 62672 elements after refining (see figure 4(b)). The corresponding time calculation and the number of nodes and all characteristics of meshing are presented in table 3.



(a) 15668 elements



(b) 62672 elements

Fig. 4. Discretization in finite elements and determination of mesh elements of the insulator 1512L

Table 3. Characteristic of the meshing

		Number of degrees of freedom	Number of nodes	Number of boundary elements	Vertex elements	Minimum element quality	Surface ratio of the element	Time calculation (S)
Number of elements	15668	62774	7860	912	208	0.714 3	$3.41e^{-6}$	3.025
Number of elements after the first refining	62672	250890	31387	1824	208	0.714 3	$3.41e^{-6}$	7.285

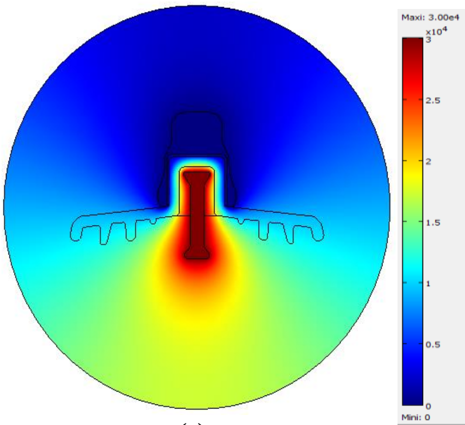
4.1. Electric potential distribution

This first part is devoted to the study of the distribution of the electrical potential on the insulator 1512L.

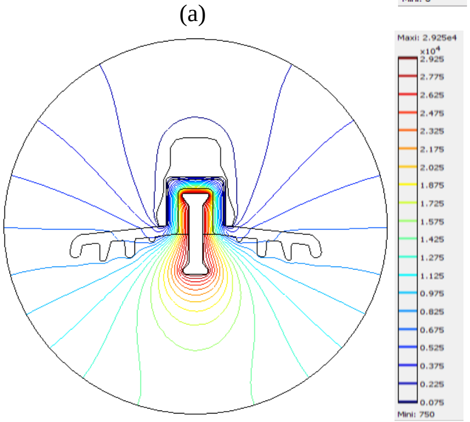
4.1.1. Influence of the conductivities

We are determining the potential distribution of the 1512L using. The following values of the conductivities σ =0, 70, 700,1200, 3000 µS/cm. The applied voltage of the line was fixed to 30 kV. It helps to simulate the behavior of the insulators of high voltage (220 kV).

Figures 5,6 and 7 show the potential and electrical potential distribution for different conductivities and the variation of the potential along the distance of leakage current for respectively different conductivities.

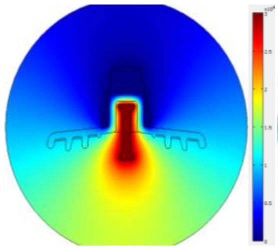


(a)

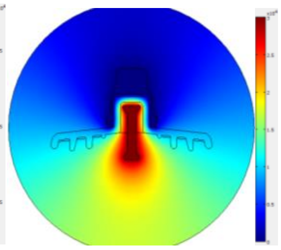


(b)

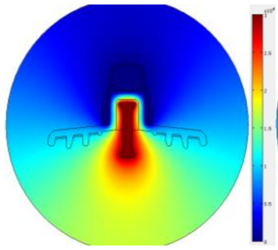
Fig. 5. Potential distribution and equipotential lines (clean model)



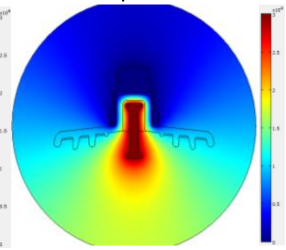
0 µS/cm



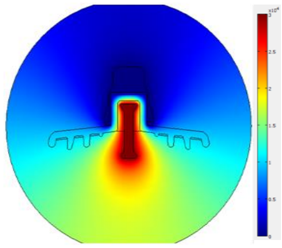
70 µS/cm



700 µS/cm

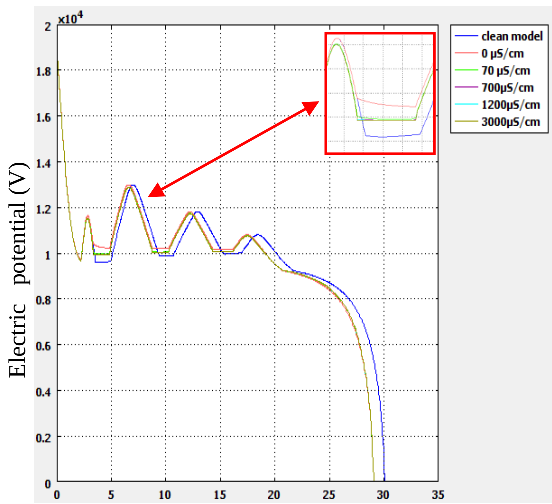


1200 µS/cm



3000 µS/cm

Fig. 6. Electrical potential distribution for different conductivities



Leakage distance (cm)

Fig. 7. Electric potential-leakage distance for different conductivities

The potential is significant to the high voltage electrode and then decreases as one moves away from the ground electrode. In the case of the clean and polluted model, 30kV is the maximum value of the voltage, shown around the active electrode, and then decreases linearly as it moves away from this electrode to the grounding electrode where the potential is cancelled. For a σ =0, 70, 700, 1200, 3000 µS/cm the curves of the potential are confused. In the clean case, the curves of the potential are closer to that of σ =0, 70, 700,1200, 3000 µS/cm. We note that the variation of the conductivity of the polluted layer has no effect on the potential along the leakage distance of the insulator. No difference was observed comparing the potential obtained for two cases: cleaned and polluted insulator.

4.1.2. Influence of the applied voltage of the line

Figure 8 presents the distribution of potential in function of the leakage distance for different applied voltage. It shows that only the values of applied voltage change but the shape remains is the same. The cap and the pin being the metallic parts. The voltage to their levels remains constant; they are the parts equipotential (active electrode (HV) and ground electrode). The variation of the potential depending on the leakage distance for different applied voltage.

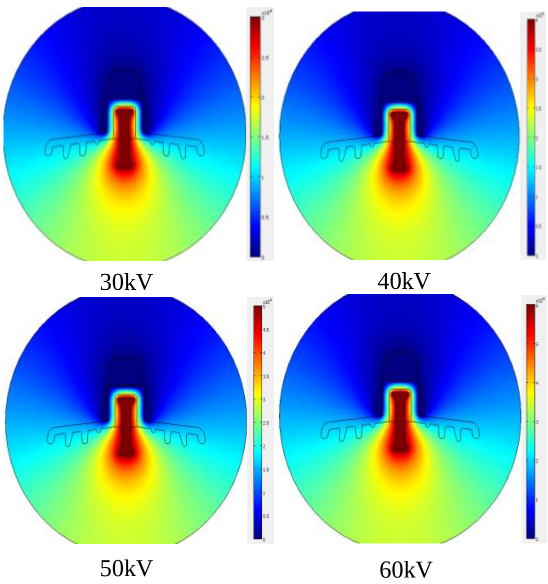


Fig. 8. Electrical potential distribution for different applied voltage of the line

Four levels of applied voltage were considered (see figure 9). We found that in function of the applied voltage of the line, the potential is distributed equitably along the leakage distance. The three curves are passing equally by three regions where the potential remains constant. It has to do with the metallic parts of the insulator.

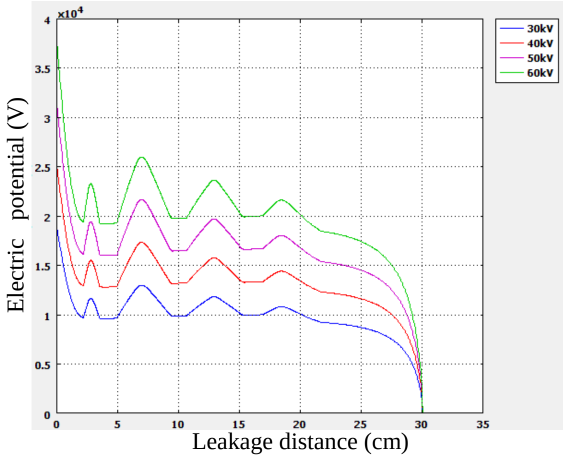


Fig. 9. Electric potential-leakage distance for different applied voltage of the line

4.2. Electric field distribution

The electric field have been investigated by many researchers [2, 4, 19-23,25-27, 29-31, 35]. In the case of the clean model, (see figure 10).
We have some findings:

Within the two electrodes (active and ground electrodes), the electric field is practically zero, because the two electrodes are conductive, the vectors of the electrical fields emerge from the activated electrode to ground electrode. The vectors as demostrated by figure10 are a tangent; we can note that the electric field is more significant with the internal dimensions of the electrodes.

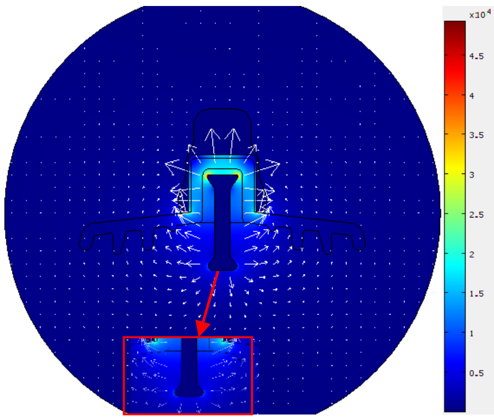


Fig. 10. Electrical (electric) field distribution for a clean model

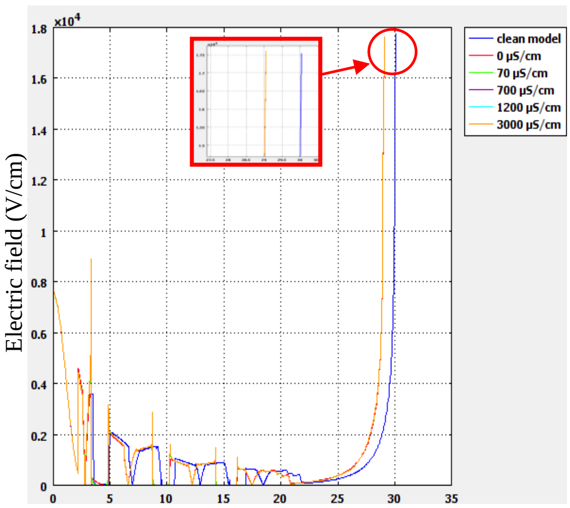
4.2.1. Influence of the conductivities

For a constant voltage of 30kV, figure 11 displays the variations of the intensity of electric field along of the leakage distance of the insulator for different conductivities. The intensity electric field is very high notably when the model is polluted, in the cap of insulator (ground). The electric field is not affected by the conditions of the surface, (polluted or clean) of the insulator.

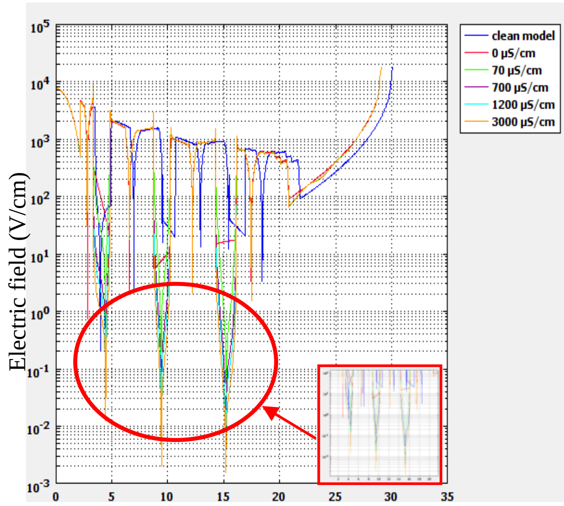
In the clean layers on the surface of the insulator, the electric field is more intense, which explains experimentally, the appearance of the electric arcs at the levels of the clean layers before the flashover of the insulator. Indeed, the electric arcs were observed in experimental studies by many researchers [4,32-35]. The electric field lines diverge from the active electrode (oriented from the HV electrode to the ends of the insulator and converge towards the ground electrode), the system becomes less rigid and the conductivity of the surface of the insulator increases. Near of the active electrode, the electric field is intense and decreases as it moves away from the active electrode and closer to the ground electrode. Also, the electric field lines diverge (from the HV (active) electrode to the ground electrode). In the near area of the active electrode, the electric field is important (relevant), and almost zero in the clean zones illustrated in (figure 11 (a)). Figure 11 (b) presented the logarithmic scale shows that in the dielectric material, the electric fields are never canceled, but takes values close to zero, (field does not disappear in the insulator but gives a very low value).

Figure 11 (a) explains the distribution of the electric field on the leakage distance for different conductivities; we notice that the electric field is prominent near the active electrode and takes the value almost zero in clean areas. (Simple scale).

We also note a slight decrease in the line of leakage distance in the polluted case compared to clean case (clean model) due to the creation of the polluting layer in the surface of the insulator. (Figure 11 (b)) is very important, says the electric field distribution in a logarithmic scale, which shows that for clean areas the electric field never cancels but takes from near zero. In this case, the interest of the logarithmic scale to explain well that in the dielectric materials the electric field never annuls, but takes values near zero.



Leakage distance (cm)
(a) Simple scale



Leakage distance (cm)
(b) Logarithmic scale

Fig. 11. Electric field-leakage distance for different conductivity
(a) Simple scale (b) Logarithmic scale

Otherwise, figure 12 shows that the conductivities have no incidence on the electric field distribution. We find that the conductivity has practically no effect on the distribution of the electric field.

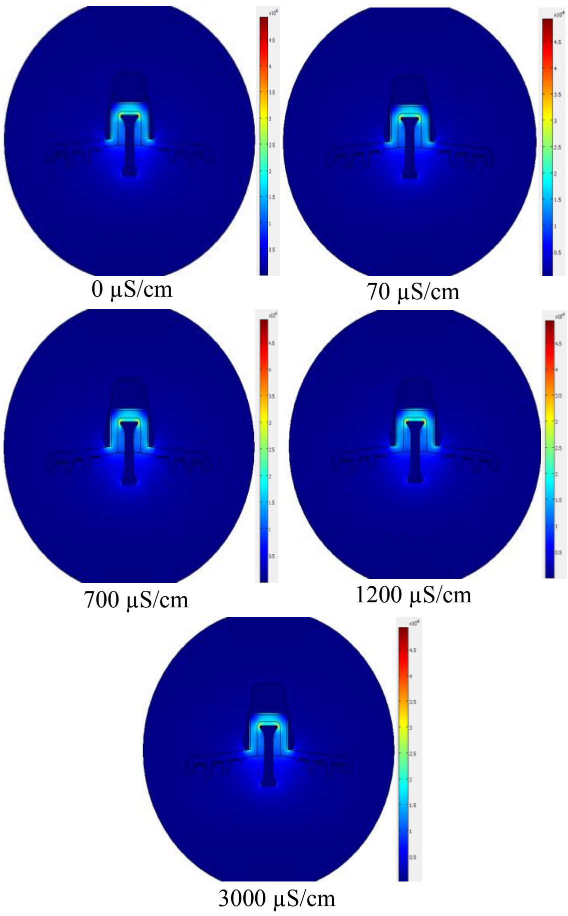


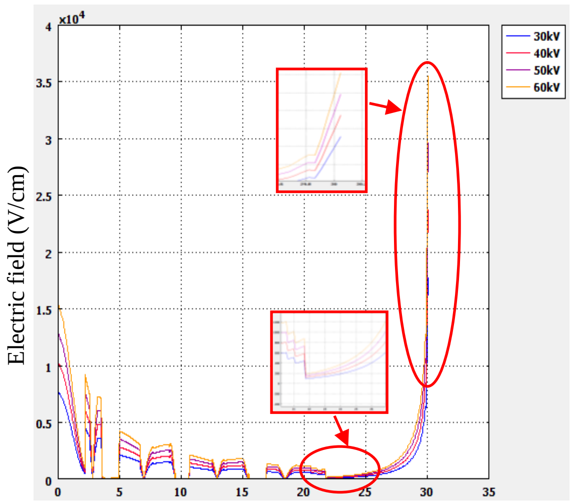
Fig. 12. Electric field distribution for different conductivities

4.2.2. Influence of the applied voltage of the line

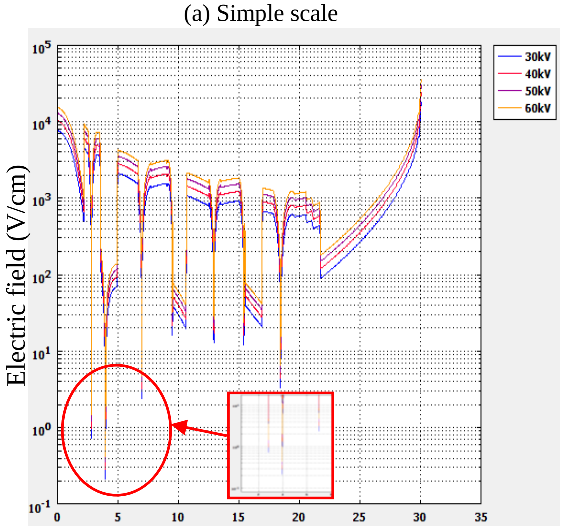
For a clean model, we present in figure 13 electric field along the leakage current distance for different applied voltage (simple and logarithmic scale).Figure 13 shows that depending on the applied voltage, only the values of the electric field changes, the shape remains the same.The increase of the applied voltage of the line increases the intensity of the electric field (figure13 (a)). Also, the insulator becomes less rigid, Indeed in the experiment, the increase in the applied voltage causes the flashover of the insulator.

We also note that electric field gets maximal values at the extremities of the insulator (cap and pin of the insulator).

Obviously, demonstrated by figure 11 (b), that the electric field never vanishes in the dielectric materials in our case, the material is the glass. However, it gives a very small value, whatever the applied voltage.(see figure 13 (b)).



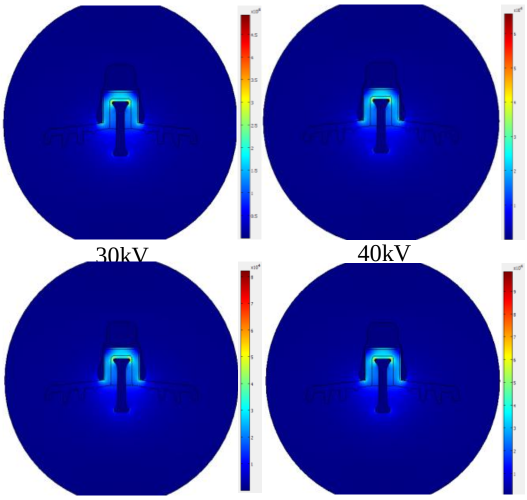
Leakage distance (cm)
(a) Simple scale



Leakage distance (cm)
(b) Logarithmic scale

Fig. 13. Electric field-leakage distance for different applied voltage

Figure 14 presents the electric field distribution for different applied voltage of the line, the increase of the applied voltage leads to the increase of the intensity of the electric field.



50kV 60kV

Fig. 14. Electric field distribution for different applied voltage

4.2.3. Influence of the rib width of the insulator

In this part, we must thoroughly estimate the model with the same radius, and practically the same shape as the real model, but with a better distribution of the field. This leads us to assume that the real model can be improved.

Our proposed system was mentioned previously by figure and table 1 where we cited its characteristics.

We are looking to change the geometry of the real insulator (1512L) by changing the length of leakage distance and keeping the same radius (R).

The results of the field thus obtained will be compared with those obtained by the real model. To see the influence of the width of the ribs ($x_{1,2,3,4}$) of the cap and pin insulator. We determine the distribution of the electric field on this insulator model, which is mentioned by figure 15.

- **Real_Model** (a) keeping our real dimensions of the cap and pin insulator 1512L, with a surface of 47.949cm^2.
- **Model_01** (c) by increasing the width of the ribs by 1.5 of its actual width, but keeping the same radius (R) as the real model, with a surface of 53.873 cm^2 .
- **Model_02** (b) by decreasing the width of the ribs by 0.5 of its real width, but keeping the same radius (R) as the real model, with a surface of 42.7028 cm^2.
- Changes in the real model, are made in a hazardous way in (figure 15 a, b, c), table 4.

Table 4. Sizing of proposed HV insulators.

Model study	Dimension	Radius, R(cm)	Glass surface (cm^2)
Real model	x'''=x =[x_1, x_2, x_3 , x_4] (fig. 15. -a-)	13.1	47.949
Model_01	x'=1.5*x=1.5* [x_1, x_2, x_3 , x_4] (fig. 15. -c-)	13.1	53.873
Model_02	x''=0.5*x=0.5* [x_1, x_2, x_3 , x_4] (fig. 15. -b-)	13.1	42.7028

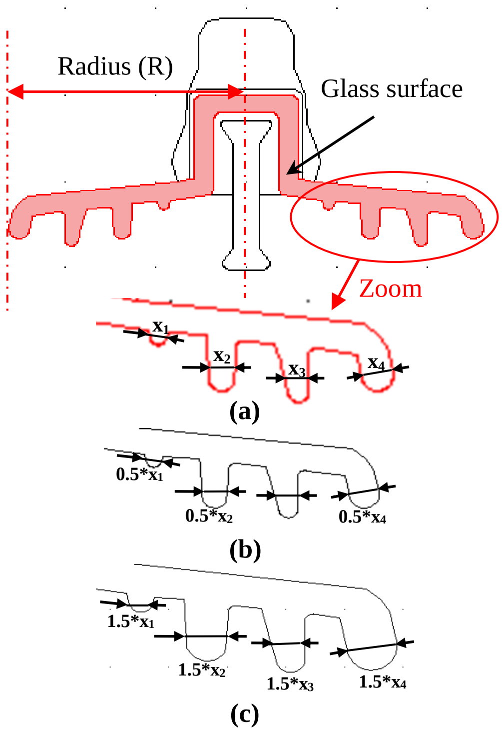


Fig. 15. Dimensioning of the ribs of the insulator 1512L.
(a)Real Model, (b) Model _02, (c) Model_01

Figure 16 ((a) simple scale, (b) logarithmic scale), shows respectively the distribution of the normal tangential component of the electric field on the insulator on the leakage distance for the three cases studied (real model, model_01, model_02), for the models indicated in table 4. We apply a voltage of 30 kV in the case of the insulator.

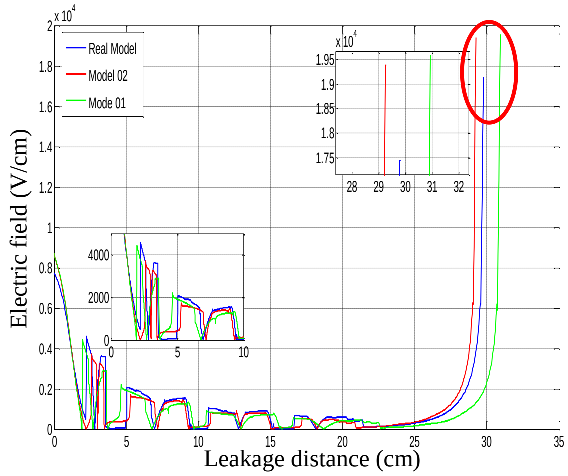
The results cited above demonstrate the importance and the influence of the geometric shape of the insulator on its dielectric behavior.

We notice that the electric field fluctuates between the cap and the pin of the insulator. It presents several local maximums. These local fluctuations and local maximums explain the appearance of localized arcs on the surface of the insulator.

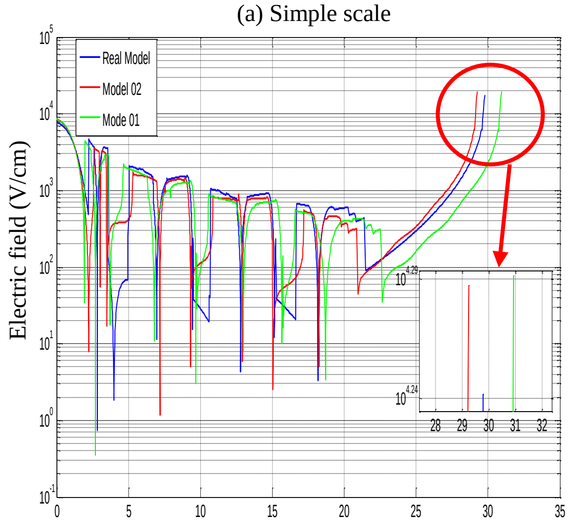
We also note that the distribution of the field on the leakage distance follows the same variations of the real model with a spatial shift due to difference of the leakage distance lengths.

In general, the shape (form) of the field distribution is similar for all models studied.

From the results carried out, the real model is the model that optimizes, the value of the electric field to the cap of the real insulator. It is optimal compared with the other two models.



(a) Simple scale



(b) Logarithmic scale

Fig. 16. Electric field-leakage distance for three studied cases (real model, model_01, model_02). (a)Simple scale, (b)Logarithmic scale

5. CONCLUSION

In summary, we have studied the electric field and electric potential distribution artificially polluted of cap and pin insulator (1512L) largely used by Algerian Society for Electricity and Gas (SONELGAZ). This study was conducted using

COMSOL multiphysics-based on the finite element method (FEM), for different electro-geometric parameters such as the influence of conductivity and applied voltage of the line under AC voltage.

The surface state which affects the distribution of the potential and the electric field and not the conductivity of the pollution. Indeed, the potential distribution is practically equitable since all the elements of the insulator will receive a very close potential difference. Moreover, the parts near the active electrode are most exposed to the electric constraints, namely, the potential difference and the electric field. The metal parts of the insulator, in this case, the cap and the pin, are equipotential and the value of the potential is always fixed. We also noted that potential and the electric field increase with the applied voltage. However, the form of the electric field and potential remain the same. In other words, the difference is in the magnitudes and not in the form. We have noted that the potential and the electric field increase augmentation in applied voltage amplitude.

The maximum value of the electric field is obtained when the insulator is polluted (3000 μS/cm). On the other hand, the effect of the surface state and the conductivity of the pollution is very negligible on the potential distribution. The performance study of a real insulator has the advantage of taking into account all the complexity of the real model for a good analysis of the physical phenomena.

The modification of the geometric shape (form reduction) of the insulator generates an increase in the electric field, then a reduction of the flashover voltage.

Finally, this by this work, the effectiveness of Comsol Multiphysics to calculate the electric field, and potential distribution of electrostatics problems have been proved.

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