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Analysis of the Electrical Field and Potential Distribution along a Distribution Line of Composite Insulator Using Finite Element Method

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Abstract: ***The insulating components of distribution line may have their characteristics compromised by several reasons such as contamination and/or moisture. Excessive electric stress combined with contaminations and moisture can be responsible for the surface arcing, which may result in insulator flashover. This paper investigates the electric field and potential distributions along surface of composite insulator under clean and metallic contamination conditions. Hematite (Fe_2O_3) contaminant has been used to analyse the impact of contamination on potential and electric field distributions along the insulator surface. In this study, a 15kV composite insulator is used and the Finite Element Method (FEM) using COMSOL MULTIPHYSICS is adopted. The simulation results allow identifying critical high field regions on composite surfaces and showing that contaminations effect on potential distribution is very weak along the insulator surface while electric field distributions are obviously depending on contamination conditions.***

Keywords: composite insulator, finite element method, electric field distribution, potential distribution, metallic contamination

1. Introduction

Composite insulators are widely used in power systems. The qualities of this type of insulators in terms of performance, particularly their behaviour under pollution in general, their low weight and mechanical strength, have contributed to their success and to their increasingly important use in electrical systems [1-3]. However, in service, they are exposed to a polluted environment close to industrial, agricultural or coastal areas. Particles in the air then accumulate on the surface of the insulator forming a pollution layer which, exposed to a humid atmosphere such as dew or fog, become conductive. The heating thus created by the leakage current results in the evaporation of water from wet surfaces and dry strip could therefore form and cause distortion of the distribution of the electrical potential and field and then the flashover of the insulator. The flashover phenomenon is one of the most complex process that occurred on high voltage insulators and whose effects can cause the breakdown of a transmission system. Furthermore, the knowledge of the electric field is helpful for the detection of defects in insulators [4].

The measurement of the electric field around a real insulator is a complex process, and even more so under polluted environment. Experimental techniques can be used but are subject to recurrent errors, which could certainly be reduced by the use of an advanced electric field detection system [5-6]. As an alternative, several researchers used numerical simulation techniques [7]. By using Maxwell's equations, electromagnetic field problems can be expressed by partial differential equations, associated to appropriate boundary conditions. These techniques include the Boundary Element Method (BEM) [8], the Charge Simulation Method (CSM) [9], the Finite Difference Method (FDM) [10] and the Finite Element Method (FEM) [11]. The FEM remains the best choice for solving potential problems with multiple dielectrics and complex geometries [12].

In many previous research studies, the electric field measurement along the insulator can also be found such as [11-15]. Doshi and al. [16] studied the distribution of the electric field along a composite isolator at different voltage levels, with and without crown rings. In [17-21], simulations were carried out with water droplets and they have been shown that volume, number and shape of water droplets on the insulator can influence the distribution of both electric field and electric potential.

However, studies on composite insulator under metallic pollution are scarce in the literature and, to our knowledge, very few studies on hematite contamination have ever been reported The purpose of this paper is to assess the contribution of the presence of a thin layer of metal pollution on the surface of a 15 kV composite insulator on the distribution of the electric field and potential using FEM through the COMSOL MULTIPHYSICS software.

2. Computational Model Building

2.1. Calculation of field distribution and electrical potential

The simplest way to calculate the distribution of the electric field is to determine the distribution of the electric potential and then to calculate the gradient of the latter in order to deduce the distribution of the electric field. The distribution of the electric field is then written as follow:

$$E = -\nabla V. \quad (1)$$

From the Maxwell equation,

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$$\nabla E = \frac{\rho}{\varepsilon_0 \varepsilon_r} \quad (2)$$

where ρ is the volume charge density, ε_0 the air permittivity (8,854 x 10-12) and ε_r the relative permittivity of the material. The Poisson equation is obtained by substituting equation (1) in equation (2).

$$\Delta V = -\frac{\rho}{\varepsilon_0 \varepsilon_r}. \quad (3)$$

If the space load $\rho = 0$, we get the Laplace equation

$$\Delta V = 0. \quad (4)$$

2.2. Finite element formulation

Assuming that the domain under consideration does not containany surface or space charge, the two-dimensional functional in Cartesian coordinates is written:

$$F(v) = \frac{1}{2}\iint \left[\varepsilon_x \left(\frac{dv}{dx}\right)^2 + \varepsilon_y \left(\frac{dv}{dy}\right)^2 \right] dxdy, \quad (5)$$

where ε_x and ε_y are the following x and y components of permittivity in cartesian coordinates and electrical potential. In the case of an isotropic distribution of permittivity ($\varepsilon = \varepsilon_x = \varepsilon_y$), equation (5)becomes :

$$F(v) = \frac{1}{2}\iint \varepsilon \left|\nabla v\right|^2 ds. \quad (6)$$

If the effect of the pollution layer is to be considered, the complex functional is written:

$$\overset{*}{F}(v) = \frac{1}{2}\iint \left(\sigma + j\omega\varepsilon \left|\overset{*}{\nabla} v\right|^2 \right) ds, \quad (7)$$

where ω is the angular frequency, σ the conductivity of the pollution layer, and $\overset{*}{F}(v)$ the complex functional.

The domain is then discretized into triangular elements with

$$v_e(x,y) = \alpha_{e1} + \alpha_{e2}x + \alpha_{e3}y; \quad (e = 1,2,...,n), \quad (8)$$

where $v_e(x,y)$ is the electrical potential of any point within the sub-domain $d\Omega$, α_{e1}, α_{e2} et α_{e3} are constant coefficients function of the triangular element e and n the number of elements. The electrical potential is obtained by minimising the functional $F(u)$, such as :

$$\frac{\partial F(u_i)}{\partial u_i} = 0 \; ; i = 1,2,..., p, \quad (9)$$

where p represents the number of nodes in the domain.
We thus obtain the matrix equation

$$\left[K_{ij}\right]\left[v_i\right] = \left\{q_j\right\} \; ; i = 1,2,..., p, \quad (10)$$

where $\left[K_{ij}\right]$ is the stiffness matrix, $\left[v_i\right]$ the vector of unknown potentials, and $\left\{q_i\right\}$ the vector that takes into account the boundary conditions.

2.3. Implementation

As the geometric structure of the insulator has a simple cylindrical shape, modelling can be simplified into a 2-dimensional (2D) problem rather than a 3-dimensional (3D) model. This makes it possible to save not only in memory but also in execution time, without affecting the accuracy. To take advantage of the axisymmetric properties of the model, only half of the insulator will be modelled, as shown in Fig. 1. The necessary parameters for the COMSOL Multiphysics program are the geometrical dimensions of insulators, permittivity, and conductivity of the materials and the boundary conditions. The electrodes are made of steel whose conductivity and relative dielectric constant are defined by $\sigma = 4.032 \times 10^6$ S/m and εr=1. The relative dielectric constant of the glass fibre core was taken equal to 7.1; its conductivity is very low, $\sigma = 10^{-14}$ S/m. The values of the conductivity and dielectric constant of the silicone fins were taken equal to 10^{-14}S/m and 4.3 respectively. A 1 mm thick layer of Hematite (Fe_2O_3) is used to analyse the impact of contamination.

Fig. 2 display the hematite particle on a shed of the composite insulator. The conductivity of the metal pollution layer is set to 2×10^6 and its dielectric constant to 18.1. The air domain was defined by a conductivity of $\sigma = 10^{-15}$ S/m and a dielectric constant of 1.0006.

The upper electrode is powered by an alternative voltage of 15 kV, while the lower electrode is connected to the ground, 0V. The area occupied by the air is chosen wide enough to minimize the effects on the potential distribution near the electrodes and along the insulator profile. On the edge of the air containment, it is assumed that there is no current or external electromagnetic source. The entire domain is discretized into triangular elements. For more precise calculation, the mesh can be refined by increasing the number of elements along the insulator surface. The computational domain is presented in Fig. 3.

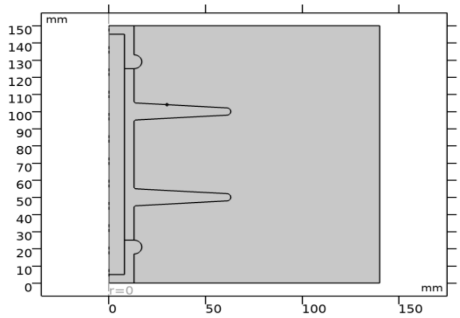

Figure 1:2D model of the polluted axisymmetric composite insulator

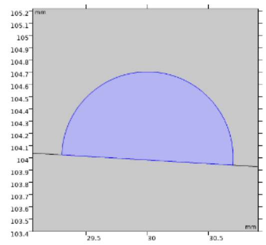

Figure 2: Zoom in view of the hematite thick layer on a shed of the composite insulator

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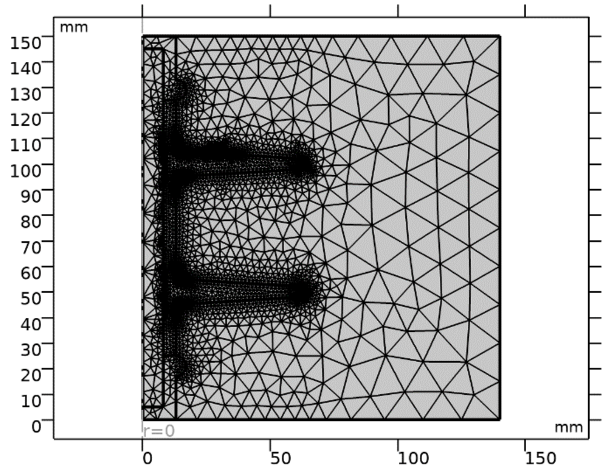


Figure 3: Overview of the 2D discretized model

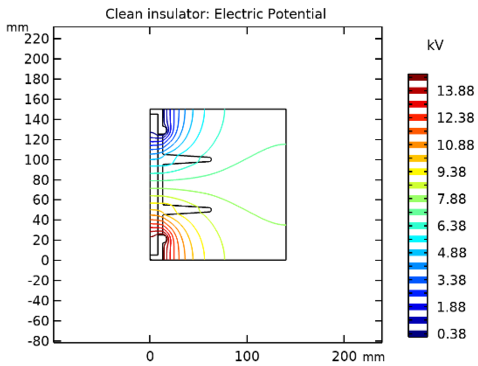
3. Results and discussions

Two series of simulations were carried out, firstly on a healthy condition and then on polluted condition. They permit to obtain the distributions of the electric field and potential for both situations.

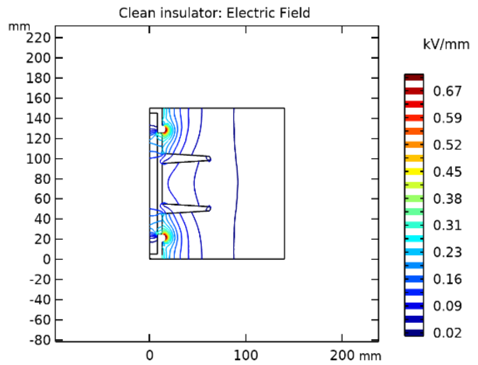
Considering the clean and healthy condition, Fig. 4(a) and 4(b) display the potential distribution and the potential along the leakage line, respectively. It can be noted that the distribution of potential is inhomogeneous and has higher amplitude close to the HV electrode. It can be observed that the distribution of the electric field is also inhomogeneous and presents a vertical symmetry at the mid-length of the leak.

The second study was carried out on a composite insulator under metallic pollution. Fig. 5(a) and 5(b) show the potential distribution and electric field stress. We note that the distribution of the potential is not homogeneous and much higher at the end close to the HV electrode respectively.

Fig. 6(a) and 6(b) display the potential distribution and the electric field along the leakage line, respectively. The figures show that the electric field is concentrated around the metal electrodes. However, the values of the electric field remain below the dielectric strength of the air and the insulator. Two field peaks can be observed at the triple points formed by the air-isolator pollution layer interfaces. It can be concluded that the presence of a small section of metal pollution layer does not influence the distribution of the electrical potential. On the other hand, it can be observing a significant local increase in the value of the electric field. The two field peaks observed at the triple point formed by the air-insulator-hematite layer interfaces show a distortion of the electric field in the presence of a low layer of metal pollution. The electric field along the insulator surface is therefore influenced by the presence of a low layer of metal pollution on its surface. This could lead to a corona effect and produce partial discharges which could lead to degradation of the insulator surface properties. Also, Like the peak effect, the rounded corners also lead to a sudden increase in the electric field. This result has been reviewed and confirmed with previous researchers [22-24].

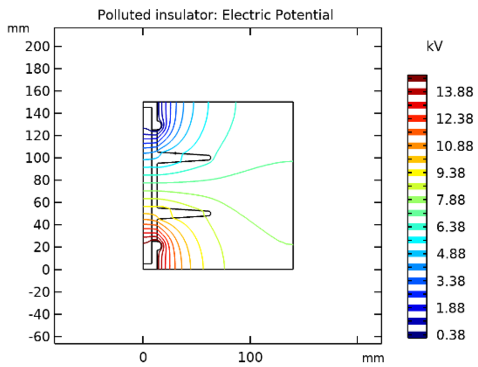


(a)

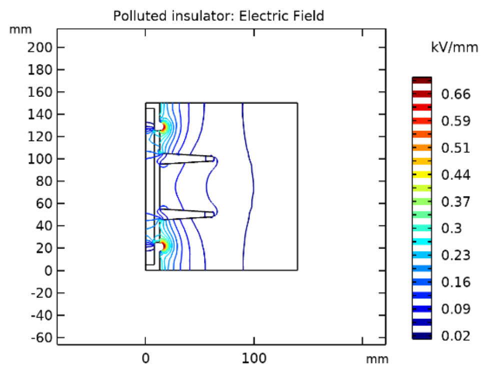


(b)

Figure 4: Clean insulator: distribution of electrical potential (a) and electric field (b)



(a)



(b)

Figure 5: Polluted insulator: distribution of electrical potential (a) and electric field (b)

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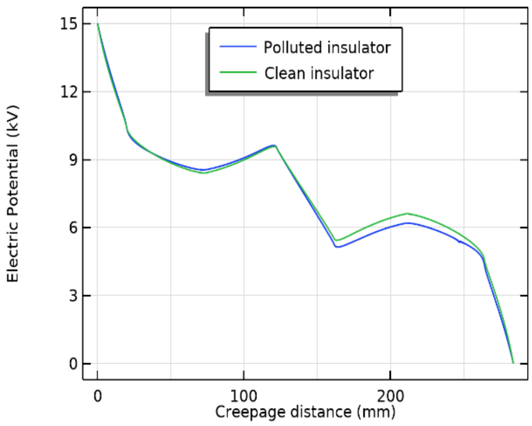
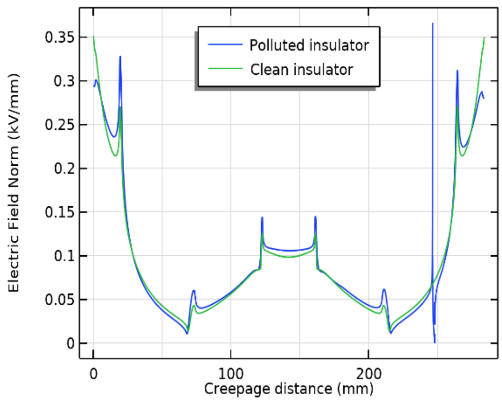


(a)



(b)

Figure 6: Distribution of the electric potential (a) and the electric field (b) along the leakage line

4. Conclusions

In this paper, a 15kV composite insulator has been analysed by using finite element method in both clean and polluted situations. It has been taking in consideration as metallic pollution, the presence of a thin layer of hematite on the insulating surface. The distributions of the electric field and electrical potential have been examined along the leakage line of a 2D insulator model. The results obtained show that the presence of a section of metal pollution layer does not influence the distribution of the electrical potential. On the other hand, it significantly modifies the distribution of the electric field locally, which significantly increases the risk of corona effects, which would cause the degradation of the insulator surface. The maximum electric field intensity is significantly obtained on the triple point formed by the air-isolator-hematite layer interfaces.

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