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Research Paper

FEM Analysis of the Electric Field and Potential of Various Types of Insulators under Uniform Pollution

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ABSTRACT

This work aims to present an analysis of the behaviour of the electric field and the potential for three different types of insulators, the glass, the porcelain and the polymeric. Since pollution is an important factor for their insulation performance and reliability in high-voltage systems, it is essential to understand how a uniform pollution layer could influence the distribution of the field and the electric potential for each of these insulators. For this purpose, COMSOL Multiphysics was used to study these distributions in both clean and polluted conditions, using the finite element method. The results show that the uniform pollution layer reduces the distribution of the electric field of insulator.

Keywords: COMSOL Multiphysics; electric field; finite element method; glass insulator; porcelain insulator; silicone insulator; uniform pollution

INTRODUCTION

The use of outdoor insulators is a vital topic for ensuring the insulation performance and reliability of high-voltage systems **(1)**. Outdoor insulators are exposed to various electric and environmental stresses, such as pollution, humidity, temperature, ultraviolet radiation, and mechanical load **(2)**. These stresses can cause degradation and aging of the insulation materials, leading to flashovers, corona discharge, leakage current, and power outages. Therefore, monitoring and improving the outdoor insulators are crucial for the integrity of the power grid.

Different types of outdoor insulators have been used in power transmission and distribution systems, such as ceramic, glass, and polymeric insulators **(3)**. Each type has its own advantages and disadvantages in terms of mechanical strength, hydrophobicity, aging resistance, cost-effectiveness, and environmental impact **(4)**. For example, ceramic and glass insulators have high mechanical strength and long service life, but they are heavy, brittle, and susceptible to pollution. Polymeric insulators have low weight and excellent pollution performance, but they are prone to degradation and aging due to their organic nature **(5)**.

The modeling of the electric field on insulators is an important topic for understanding the performance and reliability of high-voltage applications. The electric field distribution on insulators depends on various factors, such as the geometry, material, pollution, and environmental conditions of the insulators **(6)**.

One of the most widely used methods for modeling the electric field on insulators is FEM, which can handle complex geometries and nonlinear materials. FEM divides the domain into small elements and solves the governing equations at each node. FEM can also incorporate the effects of pollution, which is a major cause of flashovers and insulation failures **(7)**.

The comparison of glass, silicone, porcelain insulators based on the modeling of the electric field is a critical topic for evaluating and improving the insulation performance and reliability of high-voltage systems.

The pollution performance is an important factor for their insulation performance and reliability in high-voltage systems **(8)**. Pollution is a major cause of insulation failures and power outages in high-voltage systems. Pollution can form different patterns on the insulator surface, such as uniform, non-uniform, fan-shaped, and ring-shaped **(7)**. **Ghiasi, Faghihi (7)** used FEM to compare the electric field distribution of a 20kV polymeric insulator under clean, uniform, and non-uniform pollution with fan-shaped and ring-shaped structures. They found that the ring-shaped pollution had a more uniform field distribution with fewer thicknesses of contamination layer than the fan-shaped pollution. **Jiang, Yuan (9)** used artificial pollution tests to compare the flashover performance of various types of DC porcelain and glass suspension insulators as well as composite long-rod insulators under different pollution degrees and wetting conditions. They found that the antipollution performances of glass insulators were superior to those of porcelain insulators with the same profile. **Ghermoul, Benguesmia (10)** concluded that the presence of pollution does not distort the shape of the electric potential distribution only its value on the pin side while the value of the potential stays the same on the metal parts of the insulator starting from the cap of the first one. But the electric field distribution is distorted since the presence of the pollution even though in a uniform shape, it induces high value spikes that leads to various problems that lead to premature aging and ultimately flashover.

This research paper investigates a comparison of the electric field and electric potential behavior of three different types of insulators, under clean and contaminated conditions. The types of insulators used in this study are glass, porcelain and silicone insulators.

MATERIALS & METHODS

Mathematic Model

An easy way to evaluate the electric field distribution is to calculate electric potential distribution initially and then calculate field distribution by subtracting gradient of electric potential distribution from it.

This can be written as follows,

$$E = -\nabla V. F(v) = \frac{1}{2}\int\int\left[\varepsilon_x\left(\frac{dv}{dx}\right)^2 + \varepsilon_y\left(\frac{dv}{dy}\right)^2\right].dxdy \qquad (1)$$

From the Maxwell equation,

$$\nabla E = \frac{\rho}{\varepsilon_0\varepsilon_r} F(v) = \frac{1}{2}\int\int\left[\varepsilon_x\left(\frac{dv}{dx}\right)^2 + \varepsilon_y\left(\frac{dv}{dy}\right)^2\right].dxdy \qquad (2)$$

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).

$$\Delta V = -\frac{\rho}{\varepsilon_0\varepsilon_r}. F(v) = \frac{1}{2}\int\int\left[\varepsilon_x\left(\frac{dv}{dx}\right)^2 + \varepsilon_y\left(\frac{dv}{dy}\right)^2\right].dxdy \qquad (3)$$

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

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

The two-dimensional function F (v) in the Cartesian system of coordinates can be written as follows,

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

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

Where ε_x and ε_y are the x− and y− components of the permittivity in the Cartesian system of coordinates and v is the electric potential. In the case of isotropic permittivity distribution, the above equation can be rewritten as,

$$F(v)=\frac{1}{2}\int\int\varepsilon\left|\nabla v^{2}\right|ds\, F(v) =$$

$$\frac{1}{2}\int\int\varepsilon|\nabla v^{2}|\, ds \qquad (6)$$

If the effect of pollution layer conductivity on the electric field distribution is considered, the complex function F(v) should be taken as

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

$$\frac{1}{2}\int\int(\sigma+j\omega\varepsilon)\left|\overset{*}{\nabla}v\right|^{2} ds \qquad (7)$$

where ε is angular frequency, σ is conductivity of pollution layer µS/cm, and complex potential function.

Simulation Procedure

The COMSOL Multiphysics is a software which makes it possible to visualize the distribution of the lines of the electric field, it requires the precision of the geometry of the model. The LiveLink module made it possible to import the geometry of the insulator from the Autocad software. Figure 1 shows the geometric models of the insulators studied.

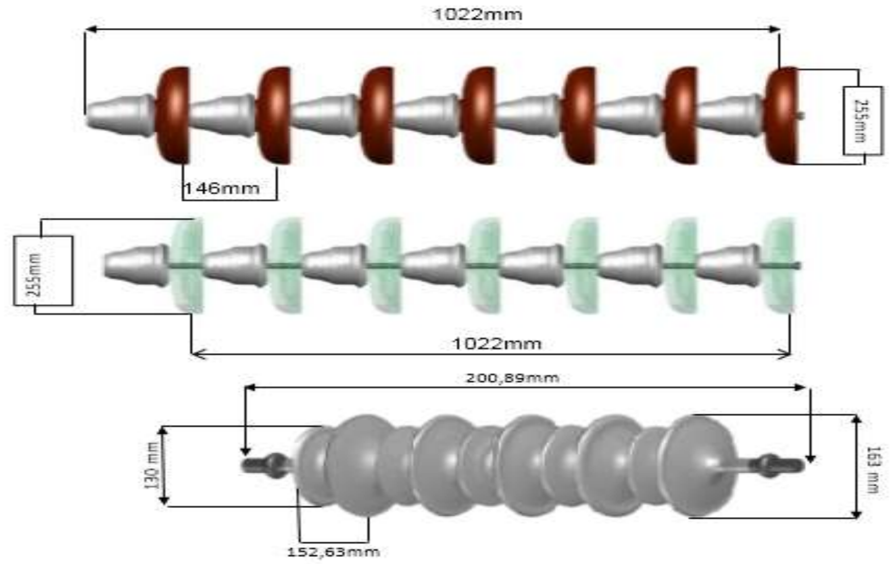


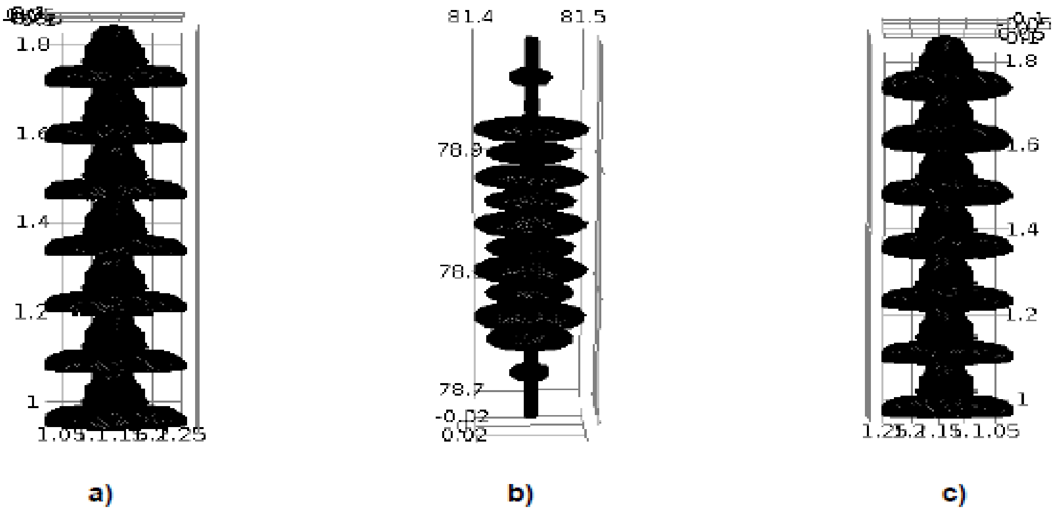
Figure 1. Geometric models of glass, ceramic and silicone insulators

We have defined the different materials of the insulators studied by introducing for each of them the relative dielectric constant Ɛr and the conductivity σ (Tab. 1).

Tableau 1. Materials properties

Materials	*Relative permittivity*	*Conductivity*
Heat-tempered glass	4.20	10^{-14}
Porcelain	6.00	0.04
Silicon	4.4	10^{-12}
Glass fiber	7.2	10^{-14}
malleable iron	1.00	$4.03.10^{6}$
Air	1	10^{-15}
Steel	1	$4.00\text{x}10^{6}$
pollution	80	$5.15.10^{-4}$

The bottom electrode is powered by an alternating voltage of 230kV, while the top electrode is connected to ground. The zone occupied by the air is chosen sufficiently large to minimize the effects on the distribution of the potential near the electrodes and along the profile of the insulator. At the edge of the air containment, it is assumed that there is no current or external electromagnetic source. It is assumed that the pollution layer has a thickness of 1mm and is uniformly distributed along the insulators. The tetrahedral shaped mesh was chosen because we are in 3D and the size of a finer degree mesh to increase accuracy (Figure2).



a) b) c)

Figure 2. Insulator mesh: a) glass, b) silicone, c) porcelain

Tab. 2 summarizes mesh characteristics.

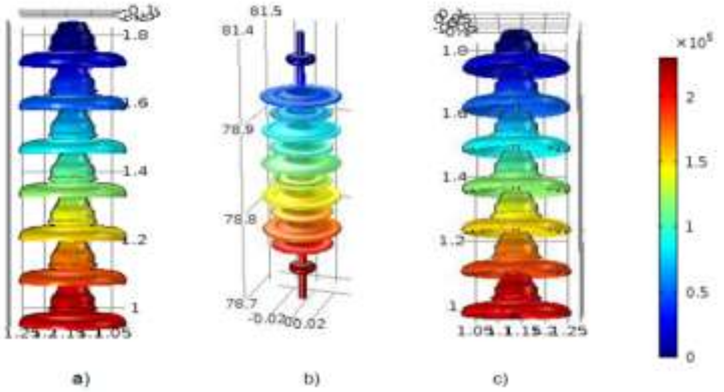
Tableau 2. Mesh characteristics

Characteristic	*Value*
Number of point elements	134
Number of edge elements	3 464
Number of border elements	147 380
Number of volume elements	1 281 616
Free mesh time	65.92s
Minimum item quality	0.000 528 5

RESULTS AND DISCUSSION

Comparison of Electric Field and Potential of Insulators under Clean Conditions

Figure 3 represents the simulation results of the voltage distribution on the surface for clean insulators (silicone, glass and porcelain). It was expected that the maximum values of the potentials are near the high voltage electrode and begin to decrease until its cancellation when one approaches the ground electrode.



a) b) c)

Figure 3. Potential distribution for clean: a) glass insulator, b) silicone insulator, c) porcelain insulator

Figure 4 shows the potential distribution along the leakage distance of insulators. It is observed that the potential distributions in both glass and porcelain insulators are almost the same, but the potential distribution in the silicone insulator is higher between the two electrodes.

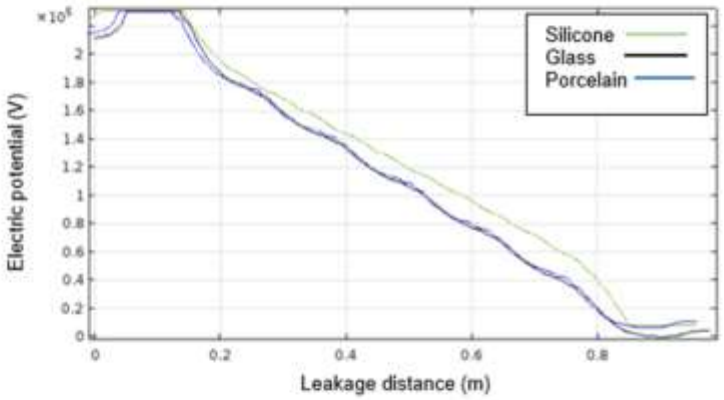


Figure 4. Potential distribution along of the leakage distance for clean insulators

Fig 5 shows the distribution of the electric field of the three insulators as a function of the leakage distance of the insulators. It is found that the electric field distributions of glass or porcelain insulators are similar. The electric field distribution is higher at the sheds for the silicone insulator. The electric field distribution along the creepage distance depends on several factors, such as the shape and geometry of the insulator, the applied voltage and frequency, the environmental conditions, and the presence of surface contamination **(11, 12)**.

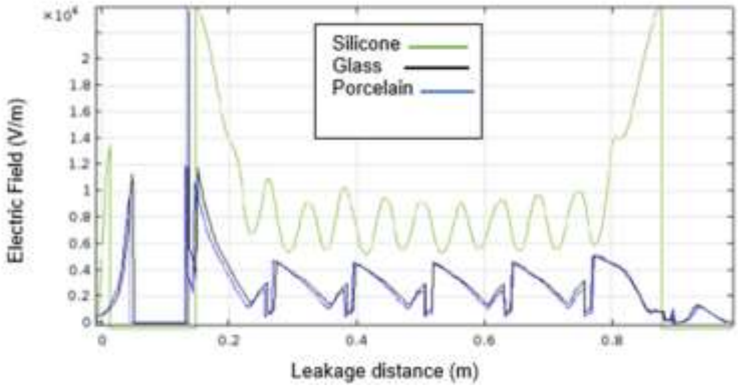
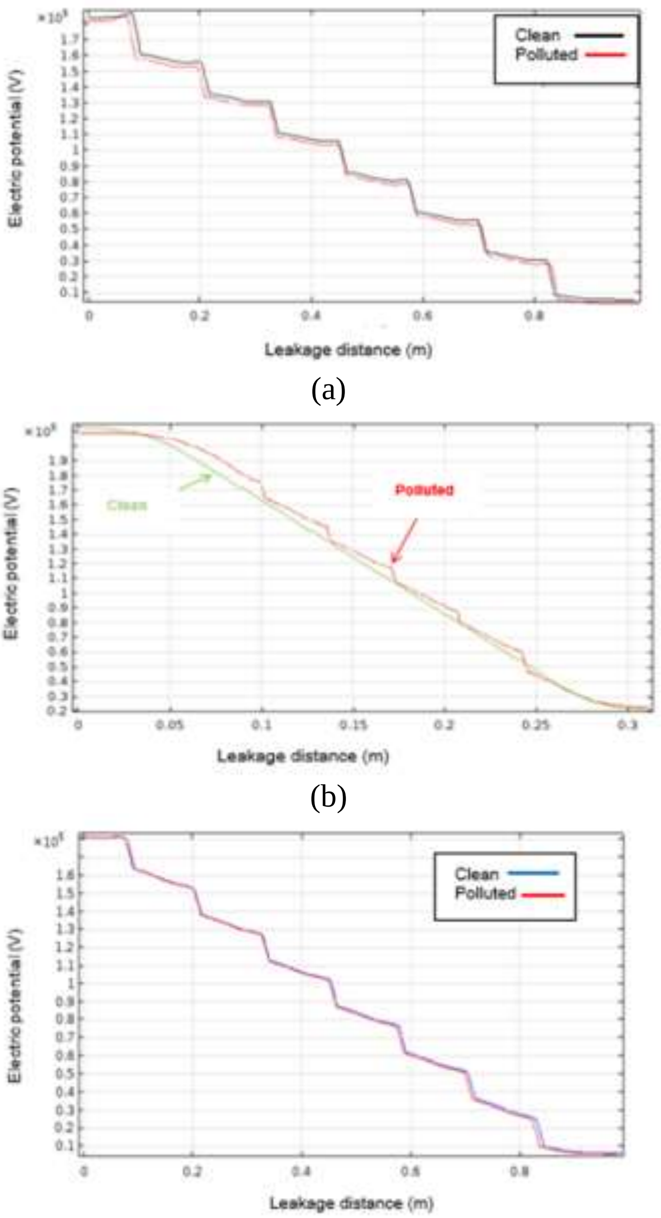


Figure 5. Electric field distribution along of the leakage distance for clean: insulators

The behaviour observed is linked to the value of the relative permittivity of the different materials. In fact, glass and porcelain have values close to relative permittivity, while that of silicon is lower. Relative permittivity is a measure of how much a material affects the electric field that passes through it. The lower the relative permittivity of a material, the more it increases the electric field inside it, compared to vacuum.

Influence of the contamination

Figure 6 shows the potential distribution along the leakage distance of polluted insulators. It is observed that the potential distributions in both glass and porcelain insulators are almost the same as in clean condition case, but the potential distribution in the silicone insulator is slightly influenced by the presence of the pollution layer.



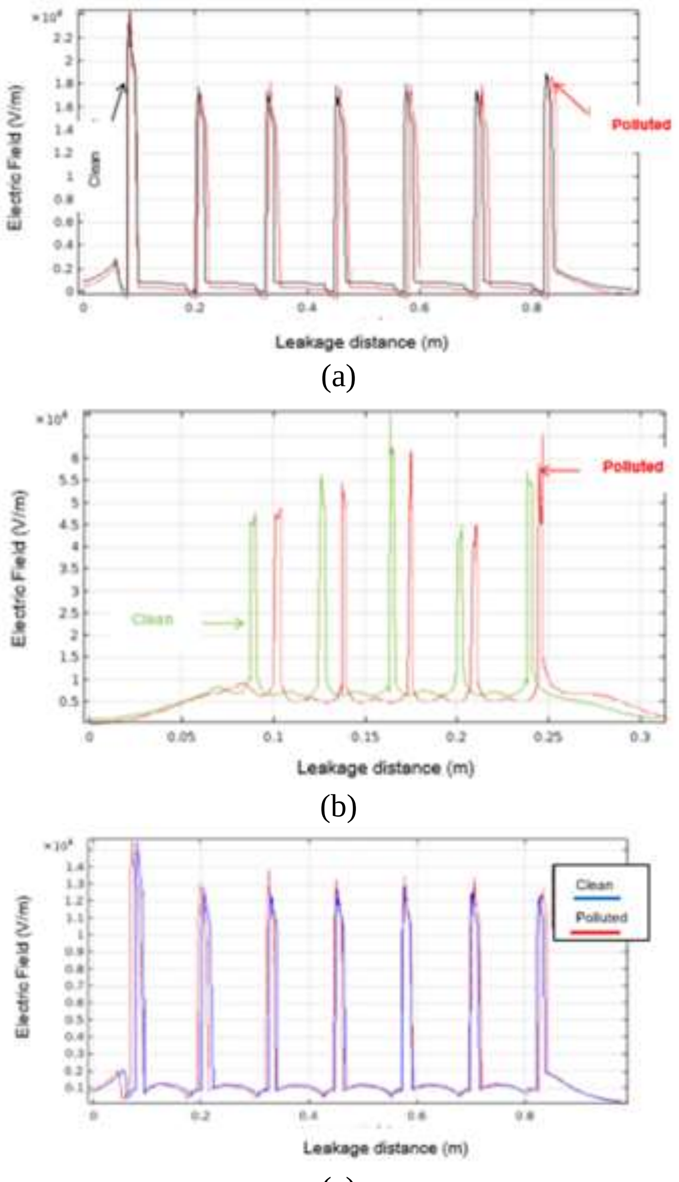
(a)

(b)

(c)

Figure 6. Potential distribution along of the leakage distance for polluted: a) glass insultor, b) silicone insulator, c) porcelain insulator

Figure 7 illustrate the electric field along the leakage line, for polluted insulators. It shows the values of the electric field remain below the dielectric strength of the air despite the presence of the pollution layer. Paradoxically, the pollution layer reduces the contribution of the electric field. This can be explained by the point effect. The pollution layer rounds the ends of the sheds of the insulators. The electric field will then be lower. A uniform contamination of the insulator is therefore beneficial for the insulator, unlike a discontinuous contamination. This behavior was observed by **Shanpeng, Youpeng (13)** who showed that the sand deposition decreases the electric field strength of insulator surface covered with sand.



(a)

(b)

(c)

Figure 7. Electric field distribution along of the leakage distance for polluted: a) glass insultor, b) silicone insulator, c) porcelain insulator

CONCLUSION

The comparison of glass, silicone, porcelain insulators based on the modeling of the electric field is a challenging and significant task for improving the design and operation of high-voltage systems. The aspects discussed above show some of the similarities and differences among these types of insulators based on their electric field distribution. However, there are also other factors that need to be considered in the comparison, such as mechanical strength, hydrophobicity, aging resistance, cost-effectiveness, and environmental impact. Therefore, further research and development are needed to provide more comprehensive and reliable results for comparing glass, silicone, porcelain insulators based on the modeling of the electric field.

Declaration by Authors

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Conflict of Interest: The authors declare no conflict of interest.

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