

A model based on the finite element method for estimating the impacts of saline pollution on high voltage insulators

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Abstract— In the course of this research, a software based on the finite element method for multiphysics simulation was employed to construct a three-dimensional model of a suspension glass insulator, incorporating its electromagnetic attributes. A layer of pollution was then modeled atop the insulator. The conductivity of the layer was changed across distinct levels to reproduce the behavior of polluted insulators tested in laboratory. The equivalent salt deposit density, the leakage current and electrical field served as reference parameters, and a relationship between them was established. The culmination of the research facilitated the creation and parameterization of a model within the multiphysics simulation software. This model allows to correlate the conductivity of the simulated pollution layer with the leakage current of the insulator, and may assist in the design and dimensioning of insulation for substations or overhead power lines, facilitating the decision making in operation and maintenance environments.

Keywords— *insulator, conductivity, equivalent salt deposit density, leakage current, electrical field, Multiphysics analysis.*

I. INTRODUCTION

High voltage insulators are part of the power electrical system and are essential for its proper functioning. They are subject to several types of pollution which can cause damage to the system and equipment that compose it [1]. Ideally, the Leakage Current (LC) in the insulator should be zero to ensure the insulation of the equipment, however, this is not true in practice. The presence of pollution can provide low impedance paths in the conductive layer of its surface, resulting in an increase in LC and a decrease in its electrical insulation capacity [2-3].

In this way, the understanding of the mechanism of LC and its relationship with the deposited pollution can be an effective way to evaluate the performance of insulators, as well as the behavior of its electrical field. Computational tools can be

used to mimic the insulators performance under a variety of pollution types, while considering the insulators geometry.

For this purpose, the Finite Element Method (FEM) stands out due to its capacity of adherence to any geometry. Furthermore, modern simulation software based on FEM allows the coupling, in the same simulation, of different physical aspects of the object under study, simultaneously.

In the FEM, the geometry of the implemented design is subjected to constraints, dividing the surface area into small parts and different shapes, such as triangular and hexagonal, according to the problem. In it, the elements form a mesh and establish connections through nodes, where partial differential equations are applied to analyze their physical behavior, obtaining an approximate result of reality [4].

In this paper, a 3D simulation model that uses a Software Based on the Finite Element Method (SBFEM) is proposed to relate the LC and the pollution condition for a given insulator geometry. This model may assist in the design and dimensioning of insulators, taking in account the influence of the pollution, based on the estimation of its effect on the LC and Equivalent Salt Deposit Density (ESDD) of the insulator.

As a detailed case study, a model implemented in a SBFEM for a 11 kV suspension glass insulator allows to correlate five diverse levels of contamination and conductivity in a saline layer over the insulators surface. The results were validated by practical experimentation data available in literature [3]. Additionally, it was analyzed the electrical field and the corresponding ESDD for each pollution intensity was calculated and related to the LC.

II. METHODOLOGY

Initially, the 3D model of the 11 kV suspension glass high-voltage insulator was built using computer-aided design software. Due to the axisymmetric geometry of the equipment, the model was built from the revolution of a 2D profile in the

SBFEM. In the drawing developed in CAD, in addition to the elements present in this type of insulator (cap, pin, cement, and glass shell), an uniform layer with thickness of 0.1 mm (arbitrarily defined) was inserted above the glass. This layer represents the pollution, and its conductivity may be changed to emulate the behavior of the pollution which is being simulated.

The model was then imported into the SBFEM (COMSOL Multiphysics, AC/DC Module), in which the properties of the materials that are present in the insulator were characterized. Each material domain was designated, and its respective relative permittivity and electrical conductivity were attributed, according to the constants in Table I [5-6].

TABLE I. PROPERTIES OF THE MATERIALS THAT COMPOSE THE GLASS INSULATOR.

Material	Relative Permittivity - ϵ_r	Electrical Conductivity σ (S/m)
Air	1.00	1.00×10^{-15}
Galvanized Iron	1.00×10^5	5.98×10^7
Tempered Glass	7.5	1.00×10^{-14}
Portland Cement	6	5.30×10^{-4}

The total simulation area, built to represent the surrounding air, had the form of a rectangle, with its boundaries potential set to zero volts, and dimensions at least 10 times larger than those of the insulator. In the insulator itself, the potential of the cap was set to zero volts, and the pin's voltage was defined as 14.14 kV_{peak}, which is the peak voltage of a 10 kV_{RMS} sinusoidal waveform. A triangular mesh, which defined the finite elements, was then used, and customized to refine the analysis of the insulator's behavior.

The pollution layer was characterized with the relative permittivity of salt (5.9). For its electrical conductivity (σ), six different values were used, where the first conductivity is 1.00×10^{-14} S/m [6], which represents the clean insulator, and the last conductivity represents the condition of most severe pollution.

The LC information and their respective associated conductivities were collected in [3], where laboratory experiments employing insulators of the same voltage class as the simulated insulator are reported.

A deposition of pollution on insulators in the field, and even in the laboratory, depends on numerous random factors and is hardly reproducible in a simulation. The thickness and distribution of the pollution layer (or drops) on the insulator shell are random and uneven, whereas in the proposed simulation, a 0.1 mm saline layer was uniformly applied along the entire insulator shell. Therefore, the use of a constant " α " was suggested to represent the effect of the real conductivity reported in [3] and compensate for these random and uneven characteristics.

The value of the correction constant α was defined based on the smallest Mean Squared Error (MSE) from a range of values tested through a sweep. As a result, it is expected that the LC values obtained from the conductivity variation in the FEM simulation would resemble those found in the laboratory by [3], which are: 0.1865, 0.2853, 0.3633, 0.4037 and 0.4898 mA. Thus, to obtain the new conductivities, the ratio between the reference conductivity and the constant α was used.

According to the determined conductivity values, their respective LC in the simulations were obtained and compared

to those from [3] using MSE to evaluate its adherence. Thus, with the determined conductivities, it was possible to calculate the ESDD to evaluate the level of pollution deposited on the insulator surface with conductivity variation. For this purpose, (1) was used, according to IEC/TS 60815-1 [7]:

$$ESDD = [(5.7\sigma_{20})^{1.03} \cdot V]/A, \quad (1)$$

where σ_{20} is the volumetric conductivity at a temperature of 20°C (S/m) applied in the simulation; ESDD is given in (mg/cm²); A is the area of a circle with 615.75 cm² of the polluted surface of the insulator; V is the volume of distilled water (cm³). For this, 500 cm³ of water with less than 0.001 S/m was used, according to IEC/TS 60815-1 [7].

At last, by obtaining the LC values and the behavior of the electrical field, it is possible to determine the relationship between them.

III. RESULTS

Based on the methodology described in this work, a three-dimensional model of the insulator was developed, along with the relationship between the established parameters: conductivity, leakage current, ESDD and electrical field.

A. Three-dimensional drawing of the insulator

The chosen insulator for the design has dimensions as found in specific datasheets [8], with a leakage distance of 380 mm and diameter (D) of 280 mm.

With the determined dimensions, in Fig. 1, the axisymmetric 2D drawing of the insulator imported into a SBFEM.

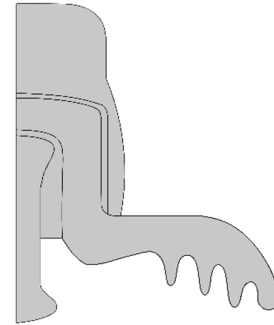


Fig. 1. Axisymmetric drawing of a hanging glass insulator in a SBFEM.

After finalizing the insulator drawing in CAD and importing it into SBFEM with mesh refinement, it was obtained the result shown in Fig. 2.

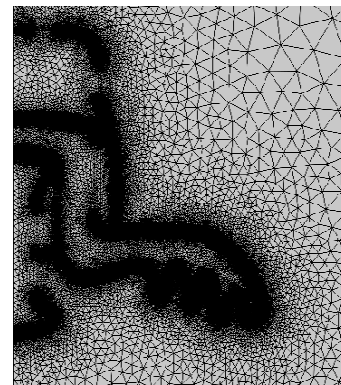


Fig. 2. Mesh used in the simulation in a SBFEM.

After the addition of the material properties of the insulators according to Table I, as well as those of the pollution layer, and the electrical properties of the insulator, the three-dimensional model of the insulator was simulated in SBFEM, as shown in Fig. 3.



Fig. 3. Three-dimensional model of the suspension glass insulator.

B. Electrical Conductivity, Leakage Current, ESDD and Electrical field

According to the ranges of constants determined in the methodology, a graph of α versus MSE was plotted to determine which α would have the best fit to determine the conductivities for the simulation, as shown in Fig. 4. It can be observed from the curve that the smallest MSE was equal to 0.0641, for the constant of 350, considering the effective voltage of 10 kV_{RMS}. Therefore, this value of α was used to determine the five conductivities used, except for the conductivity of the glass of 1.00×10^{-14} S/m, as it represents the clean condition of the insulator.

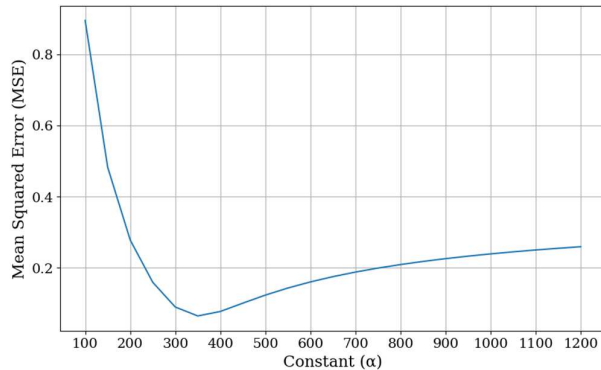


Fig.4. Graph of constant α versus Mean Squared Error.

The values of the simulated and referential conductivities are presented in Table II.

TABLE II. SIMULATION CONDUCTIVITY ACCORDING TO THE RATIO OF THE REFERENCE CONDUCTIVITY TO THE CONSTANT OF 500.

$\sigma_{\text{ref}}(\text{S/m})$	$\sigma(\text{S/m})$
2.95×10^{-2}	8.43×10^{-5}
4.67×10^{-2}	1.33×10^{-4}
6.35×10^{-2}	1.81×10^{-4}
8.43×10^{-2}	2.41×10^{-4}
12.56×10^{-2}	3.59×10^{-4}

Therefore, it was possible to simulate the LC for the new values of conductivity and compare them to the reference LC found in [3]. As seen in Fig. 5, the LC have close values to each other, with a R^2 of 0.9323. It can also be observed that,

as expected, there is an enhancement in LC with the increase of conductivity.

With the established conductivities in Table II, it was also possible to calculate the respective values of ESDD using (1). As shown in Table III, with the increase in conductivity in the simulation, there is also a direct increase in the ESDD, as observed in Fig. 5. This result was expected since the variation of LC has a direct relationship with the presence of pollution on an insulator's surface [9].

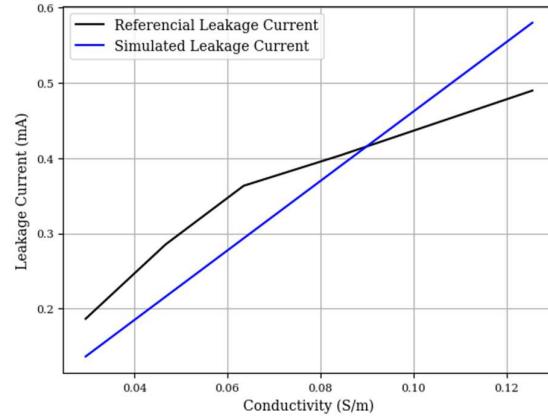


Fig. 5. Graph of reference leakage current with constant equal to 350.

TABLE III. RELATIONSHIP BETWEEN THE CONDUCTIVITY IN THE SIMULATION AND THE EXPERIMENTAL ESDD.

$\sigma(\text{S/m})$	ESDD (mg/cm ²)
1.00×10^{-14}	0.0000
8.43×10^{-5}	0.0003
1.33×10^{-4}	0.0005
1.81×10^{-4}	0.0007
2.41×10^{-4}	0.0009
3.59×10^{-4}	0.0014

In addition to the effect of pollution on LC, there is also an impact on the electrical field of the insulator. When comparing the potential surface between the highest pollution level ($\sigma = 3.59 \times 10^{-4}$ S/m) and the absence of pollution ($\sigma = 1.00 \times 10^{-14}$ S/m), a distinct behavior in the field distribution is observed. For the clean insulator, as shown in Fig. 6, the field lines are less distributed around the insulator. It is also noticeable that they are more concentrated in the region between the glass and the cement and around the pin.

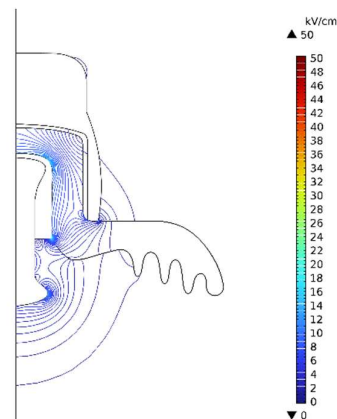


Fig. 6. Electric field distribution on the clean insulator.

However, for the higher pollution simulation, as shown in Fig. 7, the field lines are more distributed around the insulator. Moreover, they are prominent in the glass shell of the insulator, around the pin, and between the glass and cement at the top. This implies that the distribution of the electric field generates an impact with the increasing conductivity of pollution. The higher the conductivity of the pollution layer, the greater it's the effect on the uniformity of the electric field, as the behavior of the layers approaches that of a conductor.

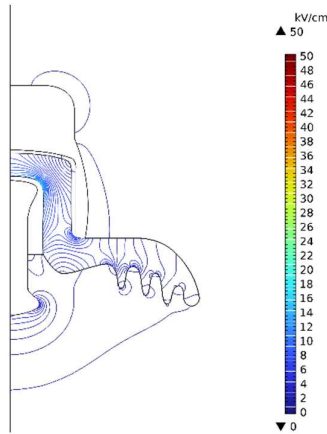


Fig. 7: Electric field distribution on the insulator with the higher pollution level.

IV. CONCLUSION

With the methodology applied in this work, it was possible to establish a model based on computational simulations, using FEM, which correlates distinct levels of contamination of a glass insulator with its conductivity. Through the literature found, it was possible to adapt, using the correction constant α with the lowest MSE, the levels of conductivity simulated in a SBFEM, to obtain LC values similar to those found in laboratory. Therefore, a graphical and meaningful relationship between the simulation parameters was established.

The behavior presented in the analyses was consistent with expectations, as with the increase in conductivity, there is a heightening in ESDD and LC. However, there is also an impact on the electrical field distribution, which is a point of improvement for the method. The use of non-continuous, randomly disposed pollution regions may give more adequate results.

With the developed model, it is possible to insert different types of pollution besides salt by changing its parameters. In addition to that, the model can adapt the pollution parameters implemented in the laboratory for simulations in an SBFEM to facilitate changes to a test that could possibly not be performed in reality, as well as to facilitate the interpretation

of data for monitoring the equipment under distinct levels of pollution. Moreover, the model could assist in the design and sizing of insulations in substations or overhead power lines, as well as in operating and maintenance environments.

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