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Comprehensive Analysis of Insulator Performance in High Voltage Transmission Systems: Implications for Efficient Power Transfer

Matiullah Ahsan[1,*], Md Nor Ramdon Bahrom[2], Zainab Zainal[3], Azrul Mohd Ariffin[4], Muhammad Saufi[1], Mohd Fairouz Mohd Yousof[1], Nor Aira Zambri[2], Farahiyah Mustafa[2], Faridah Hanim Mohd Noh[2], Aimi Syammi Ab Ghafar[2], Mehmood Ahmed[5]

[1] Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
[2] Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, pagoh campus, Johor, Malaysia
[3] Diploma Study Center, Universiti Tun Hussein Onn Malaysia, pagoh campus Johor, Malaysia
[4] Department of Electrical & Electronic Engineering, Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Kajang, Selangor, Malaysia
[5] Department of Information Technology, The University of Haripur, Haripur, KPK, Pakistan

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ABSTRACT

This research article examines the performance of insulators in high-voltage transmission systems, specifically focusing on their role in facilitating efficient power transfer along transmission lines. The study evaluates different types of insulators used in various geographical regions and assesses their withstand voltage characteristics. The research demonstrates that glass insulators outperform plastic and ceramic insulators in terms of electric field behavior. The study also investigates the behavior of AC-energized insulators in polluted and non-polluted conditions, providing insights for improving HVAC insulation design in polluted environments. The research recommends further experiments to examine insulator behavior under different applied voltage scenarios. Overall, the study emphasizes the importance of insulators in high-voltage transmission systems and provides valuable insights for developing advanced insulator technologies to enhance power transfer efficiency.

1. Introduction

Insulators are a crucial component in power systems that are used for transmitting electricity over long distances. They support overhead lines and prevent them from coming into contact with supporting structures, which ensures efficient and safe transmission of electricity. Traditionally, ceramic and glass materials were used to make insulators. However, in the late 1970s and mid-1980s, insulators made of polymers became popular for certain constructions. According to Das *et al.,* [2], ceramics were widely used for insulator production between the mid-1960s and 1980s.

Das *et al.,* [2] have also identified various types of insulators, including pin, suspension, strain, and shackle insulators. When selecting an insulating material, reliability should be the primary factor

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[*] *Corresponding author.*
E-mail address: he210038@student.uthm.edu.my

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to consider whether it is a composite or ceramic insulator. Although shackle insulators were previously used mainly as strain insulators, they are now commonly used in low-voltage distribution networks. It is widely agreed that high area intensity and voltage supply can result in problems such as crown, partial discharge, premature aging, or flashover. Insulators in control transmission lines are exposed to various factors over time, including lightning overvoltage, switching, thermal stresses, and aging. [2]

Furthermore, as stated by Shea *et al*., [3], it is widely accepted that polluted insulators operating under service voltage are prone to flashover due to unfavorable environmental conditions. A layer of Pollution accumulates on the insulator's surface, and the presence of dew or light rain can create a moist conducting pathway. It leads to the flow of leakage current on the insulator's surface, ultimately causing flashover.

2. Literature Review of Insulators

According to research by De Teresa *et al.,* [4], non-ceramic insulators are better than porcelain insulators. These insulators have excellent surface properties in wet conditions and are mechanically strong and lightweight, as noted by Youn *et al.,* They also resist vandalism and require less maintenance costs [6]. However, non-ceramic insulators can undergo chemical changes, experience erosion, and tracking, and have a limited lifespan. Additionally, detecting faulty insulators can be a challenge, as shown in Figure 1. Several authors have published review papers on insulator properties [7,8].

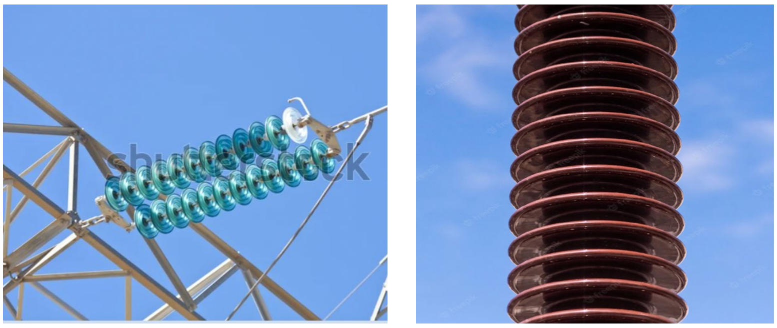


Fig. 1. Glass and Porcelain insulator

Electric fields can cause non-uniformity in the distribution of electric fields, especially on the surface of insulators, according to a report by Lindsey *et al.,* [9]. Dry Pollution does not affect the transport of electric fields, unlike clean conditions. A study specifically examined the effects of two types of impurities, pressed wood and concrete cleaning, on insulator surfaces. Identifying faulty insulators can be difficult, as shown in Figure 1. Several authors have published review papers on the effect of insulators on Pollution, which can be found in papers [10,11].

In 2015, Yang *et al.,* conducted a research project in partnership with a simulation laboratory to study the initiation of corona discharge and improve the electrical field by utilizing polymer insulators in practical settings. The study employed a computer simulation technique that used finite elements to model an insulator. The experimental conditions were designed to replicate the humidity levels present on the insulator's surface. The findings revealed how specific service conditions can elevate the electric field.

The dimensions and dispersion of electrical fields vary depending on the material and are influenced by several factors, including the shed configuration, applied voltage magnitude, and environmental conditions. If the insulator is contaminated, the corona onset experiences a field increase. The data indicates that current service conditions can enhance the electric field. By utilizing modeling and field calculations, designers can identify vulnerable areas, leading to improved isolation coordination and reduced disruption.

This article discusses the difficulties associated with researching ceramic, plastic, and glass insulators that are employed in electrical systems. It presents two techniques for assessing the electric field distribution along non-ceramic insulators, which is vital for optimizing their performance. The study employs Ansys Maxwell software for simulations, which provides valuable insights into insulator behavior without the need for excessive physical testing. The ultimate goal of this research is to improve the efficiency and reliability of insulators used in transmission and distribution lines.

2.1 Finite Element Method

Palit *et al.,* [13] have published a paper stating that Finite Element Analysis (FEA) is a powerful computational technique used to solve complex mathematical problems. FEA is particularly effective in dealing with continuous entities that have an infinite number of degrees of freedom. FEA modeling aims to simplify these problems by breaking them down into discrete elements. These elements, often triangular or quadrilateral in shape, interact based on various physics research parameters. Accurate simulations rely on the voltage potential and dielectric permittivity of the electrostatics model. Linear or quadratic functions are commonly used to approximate the solution for each element. Figure 2 shows an overview of the general procedures involved in FEM Simulation. By assembling a Galerkin matrix for each element and combining them, the intricate model can be solved efficiently. Several authors have published review papers on Finite Element Analysis (FEA), which can be found in papers [15–16].

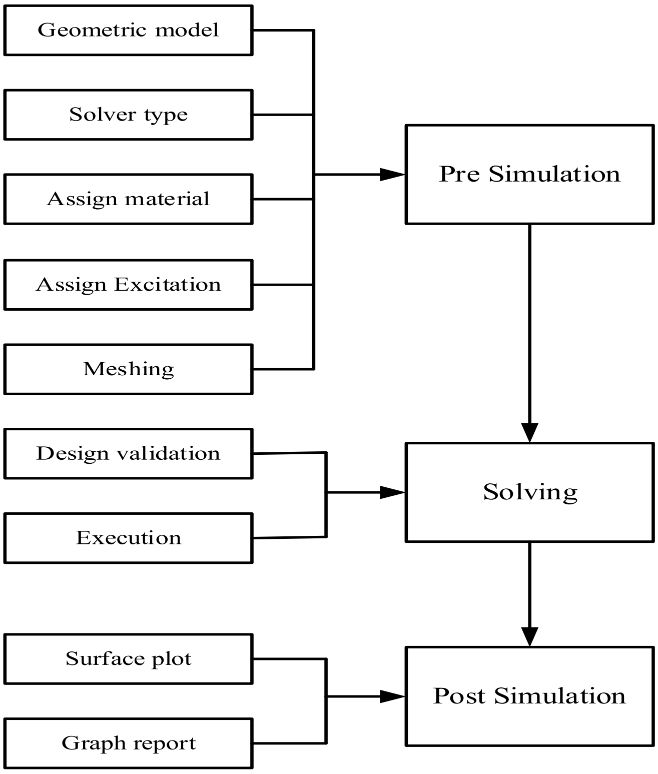


Fig. 2. Flow chart of the procedure of FEM

3. Methodology

This research focuses on designing and meshing insulator models using the finite element method, selecting model materials, and finding electric field stress on insulator models; in Ansys Maxwell, the procedure is shown in flow chart Figure 3.

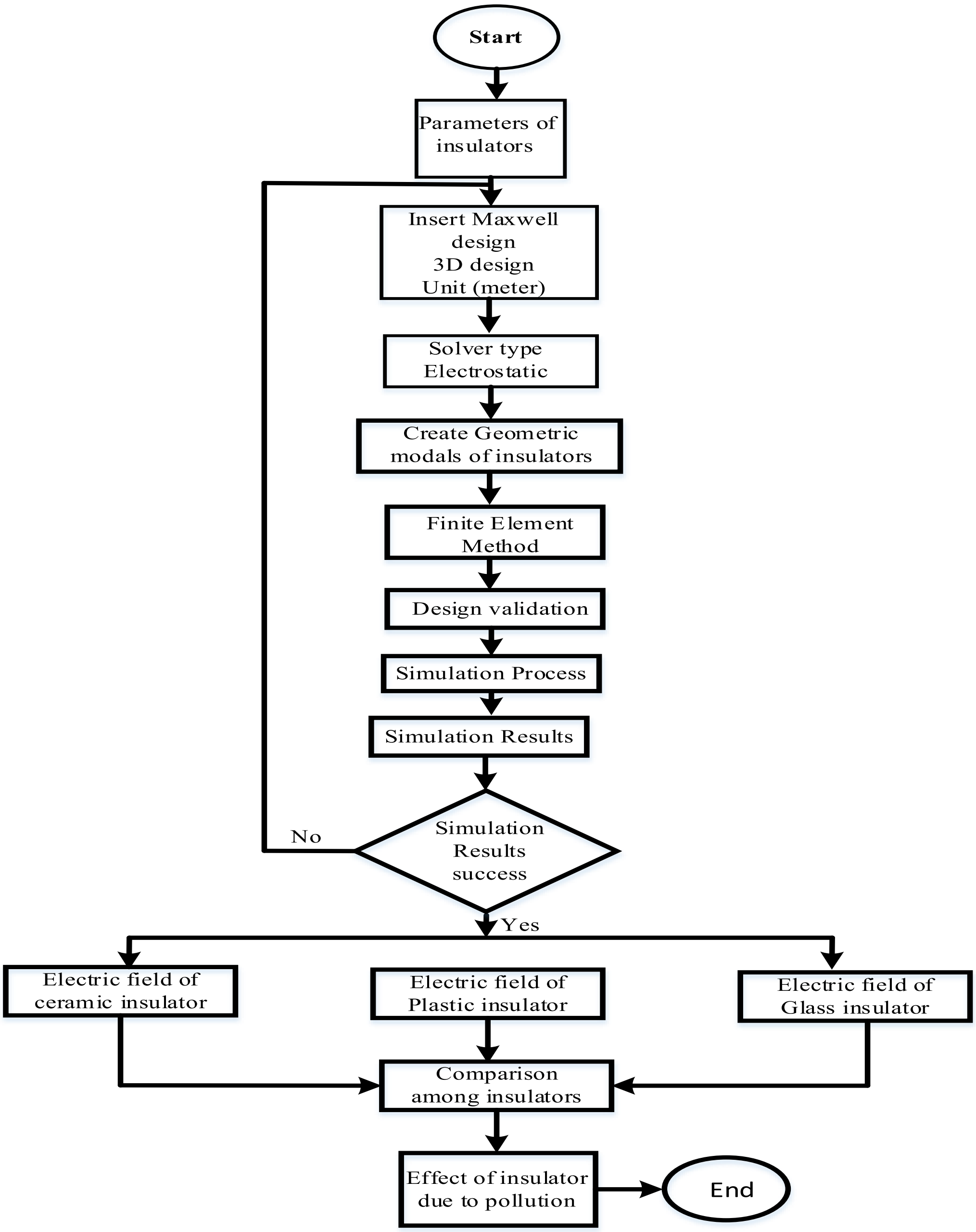


Fig. 3. Flow chart of the methodology

3.1 Modelling and Simulation with Ansys Maxwell

Finite element method modeling is using ANSYS Maxwell based on the following procedures, shown in Figure 4:

i. The geometry of the model is designed in ANSYS Maxwell.

ii. Boundary value conditions are defined to specify the properties of the materials used in the model. Additionally, the physics requirements were provided.
iii. Meshing and refinement are done to ensure that the final solution is independent of the meshing size by dividing the model into discrete elements.
iv. Solution and visualization, extracting data, and presenting the findings models.

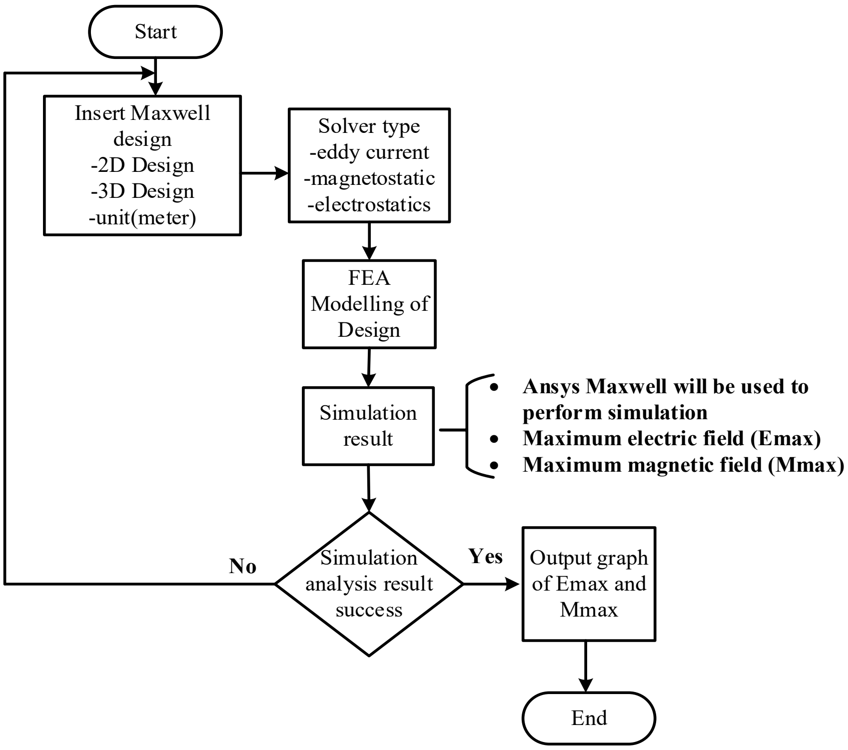


Fig. 4. Flow chart of finite element analysis

3.2 *Maxwell Equation*

According to Austin *et al.,* [16] that the Ansys Maxwell software is commonly utilised in the design of 3D insulators, analysis of electric fields, and evaluation of polluted insulators. The software utilises Eq. (1) to Eq. (4); the detailed equations on the Ansys Maxwell are published in the papers [16-18].

$$\nabla \times H = J + \partial D\ \partial t \tag{1}$$

$$\nabla \times E = -\ \partial B\ \partial t \tag{2}$$

$$\nabla \cdot D = \rho \tag{3}$$

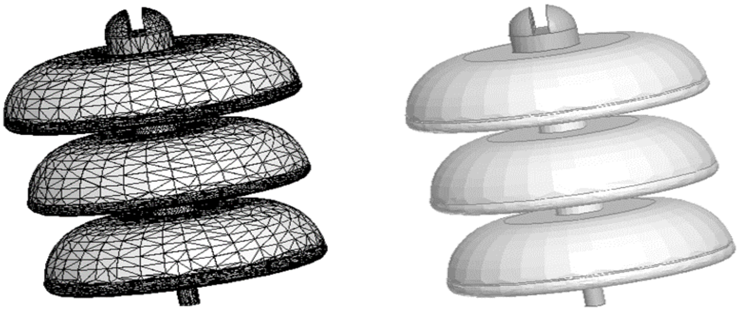
$$\nabla \cdot B = 0 \tag{4}$$

Where
E represents the magnitude and direction of the electric field.
D represents the electric displacement in the given context.
B represents the magnitude of the magnetic field's flux density.
H represents the magnetic field intensity, denoted in units of amperes per metre (A/m).
J represents the density of the conduction current.

ρ represents the charge density.

3.3 Mesh and Boundary Setting

Birlasekaran *et al.,* [19] published papers stating that the Maxwell mesh creator generates a mesh based on predefined mesh operations. Several authors published the details about the mesh in [19-24]. A mesh operation establishes criteria for a designated set of objects, which the mesh maker uses to generate meshes that meet those criteria. Initially, Maxwell produces a mesh that approximates the surface. If any difficulties arise, the Mesher automatically undertakes necessary repairs to ensure an accurate mesh representation of the model. The solution profile provides information about the performed mesh repairs, and the outcomes are displayed on a per-object basis in the mesh statistics window. During this procedure, mesh refinement is carried out using predefined mesh operations, as shown in Figure 5.



(a) (b)

Fig. 5. (a) Mesh and (b) model

From the mathematical standpoint, according to Yusefi *et al.,* [25], it is crucial to include boundary conditions in order to ensure the singularity of the solution obtained by Maxwell's equations. Akter *et al.,*[26] also published a mathematical standpoint about boundary conditions.

Boundary conditions serve as a convenient way to represent different ideal scenarios in modeling, allowing for the simulation of the electromagnetic field within a dielectric material between two conducting elements. In this case, it is only necessary to model the two surfaces in contact with the dielectric, incorporating appropriate boundary conditions on the top and bottom surfaces. This approach enables accurate field simulation within the dielectric without explicitly depicting the corresponding conductors, as shown in Figure 6. Final models of glass, ceramic, and porcelain insulators are shown in Figure 7.

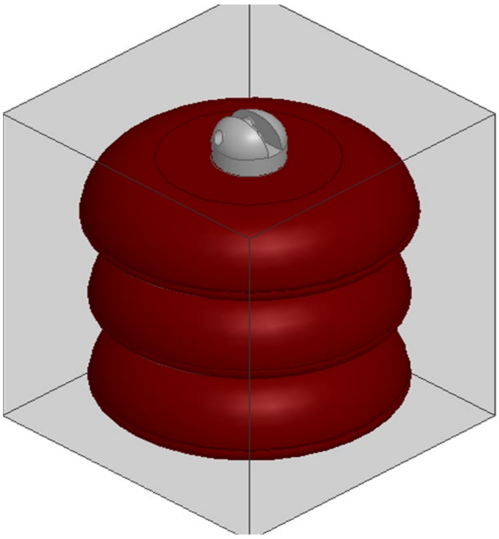
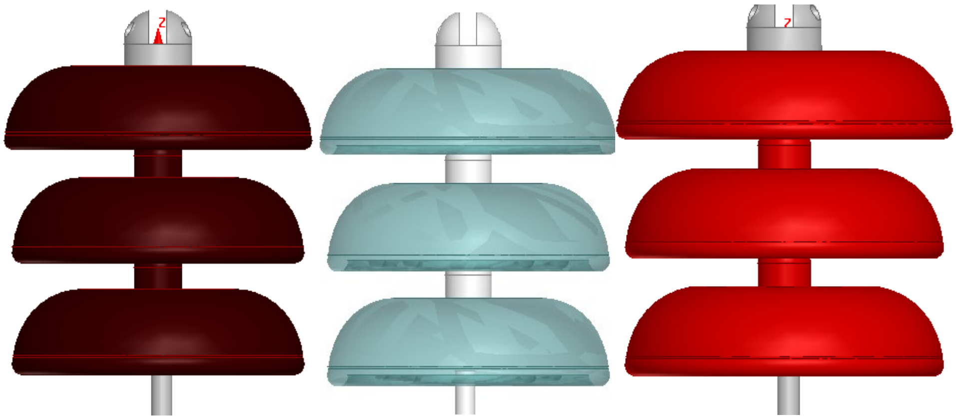


Fig. 6. Boundaries used in a simulation



(a) (b) (c)

Fig. 7. Insulator modal (a) porcelain (b) glass and (c) ceramic

4. Simulation and Results

Porcelain, polymer, and glass insulators are simulated to detect electric fields and evaluate the proximity of contaminated particulate matter on their surfaces. This assessment helps identify areas where electric fields or power fluctuations may increase along the insulator surface.

4.1 3D Results

In the simulation, the following parameters were applied to porcelain, glass, and plastic insulators: All other parameters are the same except for relative permittivity, as shown in Table 1.

Table 1
Parameters of Insulators

Height of Insulator	1000mm
Diameter of Insulators	80mm
The diameter of the insulator shed	200mm
The space between the two sheds	21mm
Diameters at the top and bottom	135mm
Glass's Relative Permittivity	5.6
The relative permittivity of ceramic	3.2
The relative permittivity of plastic	5.2
Conductivity	0 Simens/m

4.1.1 Model of insulator

In the Figure below, 33kV voltage is given to the bottom of the insulator, and the top is grounded, as shown in Figure 8.

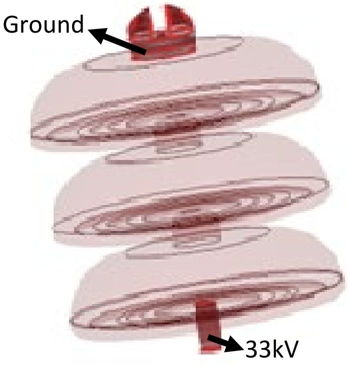


Fig. 8. Excitation to Insulator

4.1.2 Electric field plot and graph of glass insulator

The electric field plot in the model's Figures 9 and 10 of Ansys Maxwell shows the electric field distribution of the insulator in the region where there are five offset points. The red areas have the highest electric field, while the blue areas have the lowest and no electric field. The electric field distribution on the various insulator discs is now under discussion.

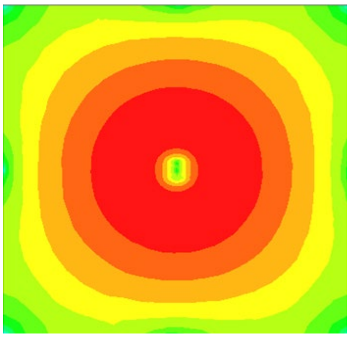


Fig. 9. Electric Field plot

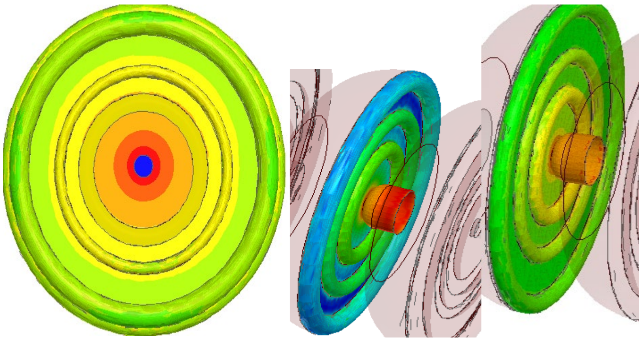


Fig. 10. Electric Field distribution on discs

In the diagram, the red region represents the area with the highest electric field intensity. This component is located near the high-voltage source, which produces the strongest electrical stress. Meanwhile, the green region indicates areas with a relatively weaker electric field intensity compared to the red region. The phenomenon observed suggests that the electric field magnitude decreases as the distance from the high-voltage source increases but still maintains a higher value than the blue region. The blue region, on the other hand, signifies areas with minimal to non-existent electric field intensity. Furthermore, the black ring in Figure 11 highlights the electric field values on all the insulators that are considered for investigation. The highest value is 156.701×105kV/cm.

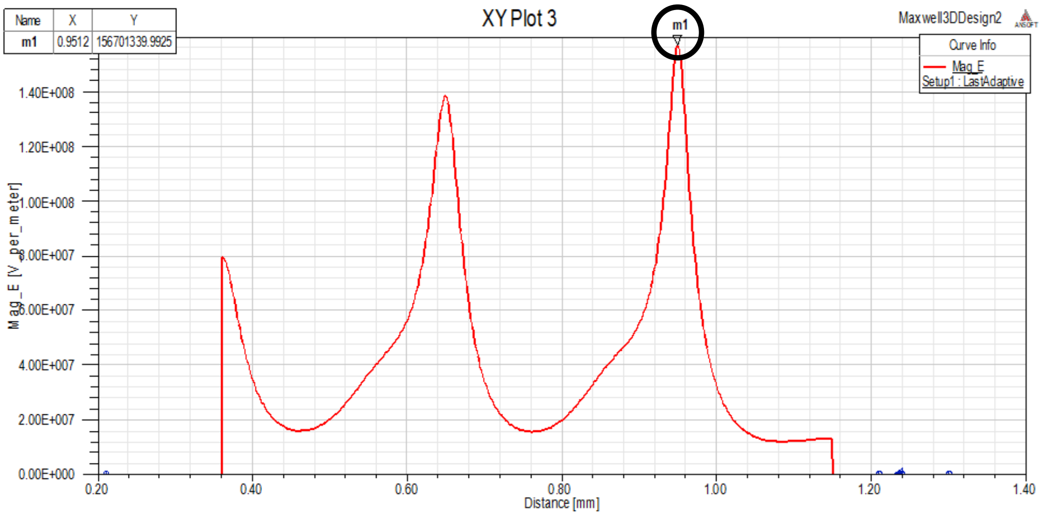


Fig. 11. Graph of Glass insulator

4.1.3 Electric field plot and graph of a ceramic insulator

Figure 12 shows the electric field distribution plot of ceramic insulators, showing three regions of colors that are the same as the glass insulator but with different values.

The electric field value in the circle (Figure 13) demonstrates the highest value of the ceramic insulator, which is 137.738×10^{5}kV/cm.

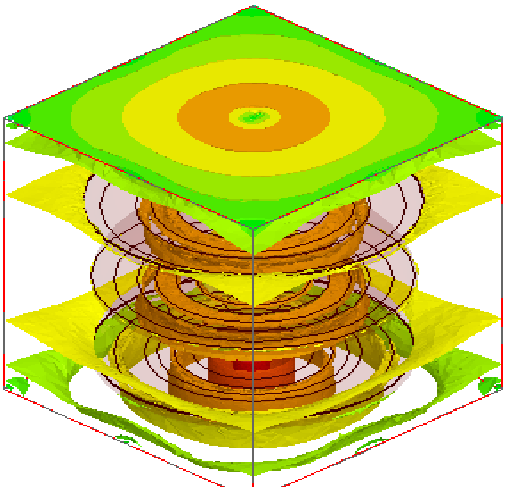


Fig. 12. Electric Field on different discs

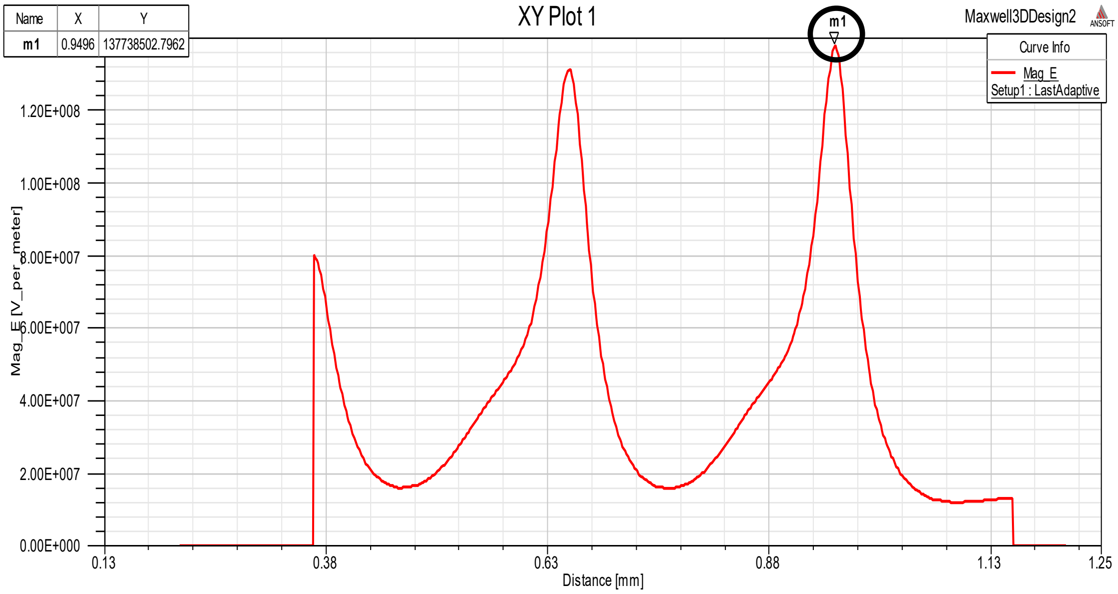


Fig. 13. Electric field graph of ceramic material insulator

4.1.4 Electric field plot and graph of plastic insulator

Figure 14 shows the electric field distribution plot of plastic insulators, showing three regions of colors that are the same as the glass insulator but with different values.

The electric field value in the circle (Figure 15) demonstrates the highest value of the plastic insulator insulator, which is 126.225×10^5kV/cm.

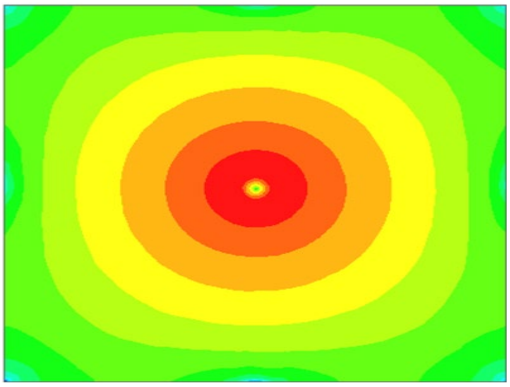


Fig. 14. Electric field of Plastic Insulator

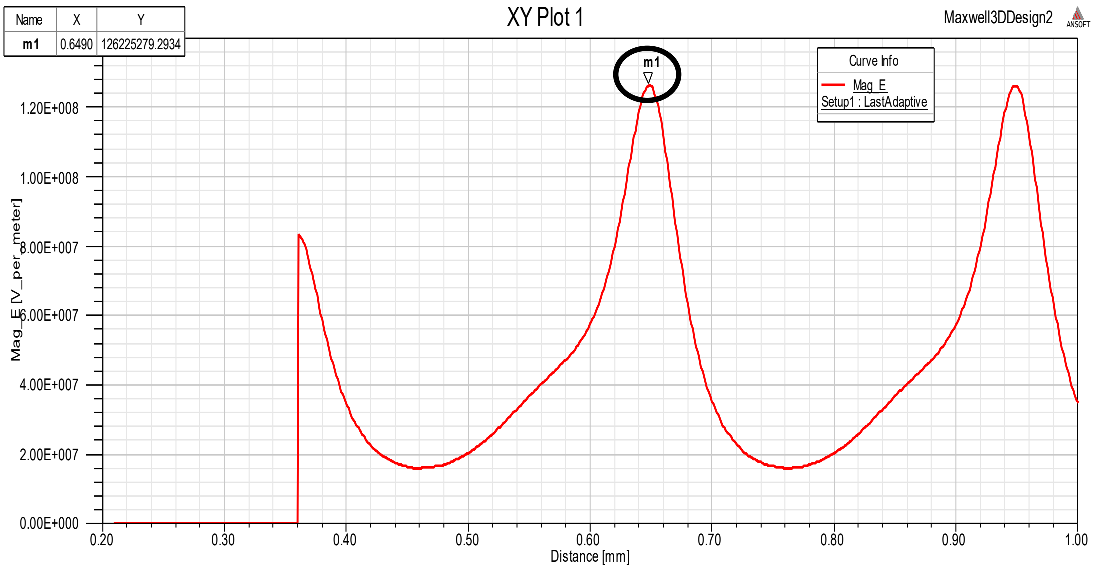


Fig. 15. Graph of plastic insulator

4.1.5 Comparison among insulators

In this study, three different types of insulators made of glass, porcelain, and plastic were analyzed to determine their peak electric field values. The results were graphed, and the highest values were compared. The data shows a consistent variation in the values obtained from each insulator. The electric field values obtained from the various insulator graphs are presented in Table 2 and Figure 16.

According to Figure 16, the glass insulator exhibits the most significant electric field magnitudes compared to the ceramic and glass insulators. On average, there is a 15% higher compared to plastic and ceramic insulators.

Table 2
Electric Field distribution of three insulators

Material	Peak electric Field values (kV/cm)
Glass	156.7×10^5
Ceramic	137.7×10^5
Plastic	126.6×10^5

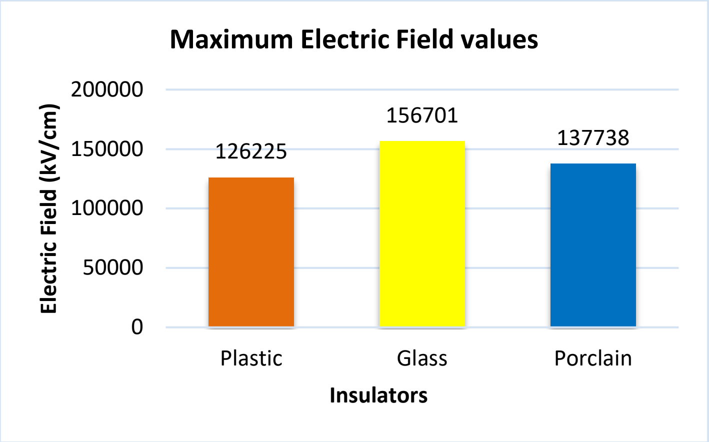
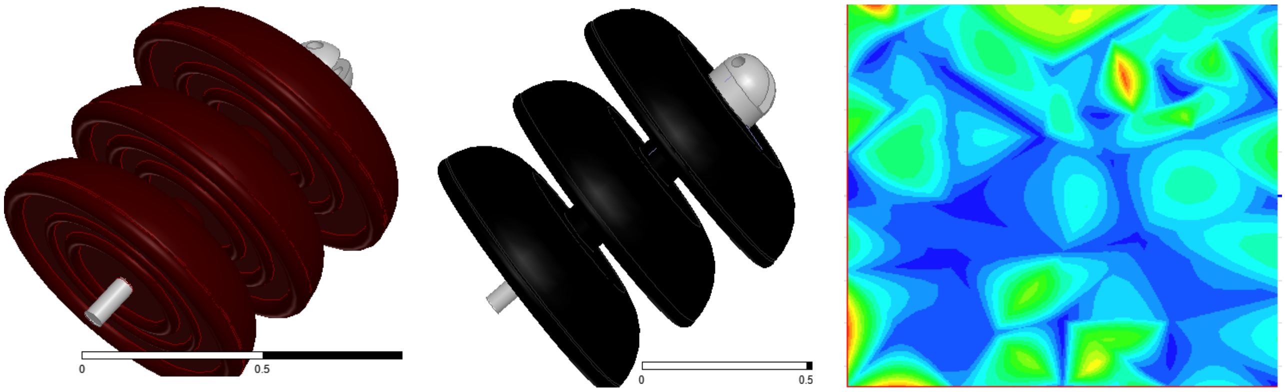


Fig. 16. Maximum Electric Field

4.2 Effect of Insulators due to Pollution

A 2 mm thick pollution layer overlaps can be seen over the outside of the insulator in Figure 17(b), as indicated by the dark shading.

Figures 17(c) and Figure 18 show the propagation of electric fields across the surface of a contaminated insulator. The X-axis pivot denotes the vertical extent of the insulator's surface. The electric field's value exhibits a rapid increase followed by a gradual ascent towards the top of the insulator, as is evident. The graph shows dissimilarities compared to the clean and recently manufactured insulators depicted in the figures. The investigation of the electrical field on ends has not been considered.



(a) (b) (c)

Fig. 17. (a) Clean and (b) polluted insulator and (c) Electric field distribution over polluted insulator

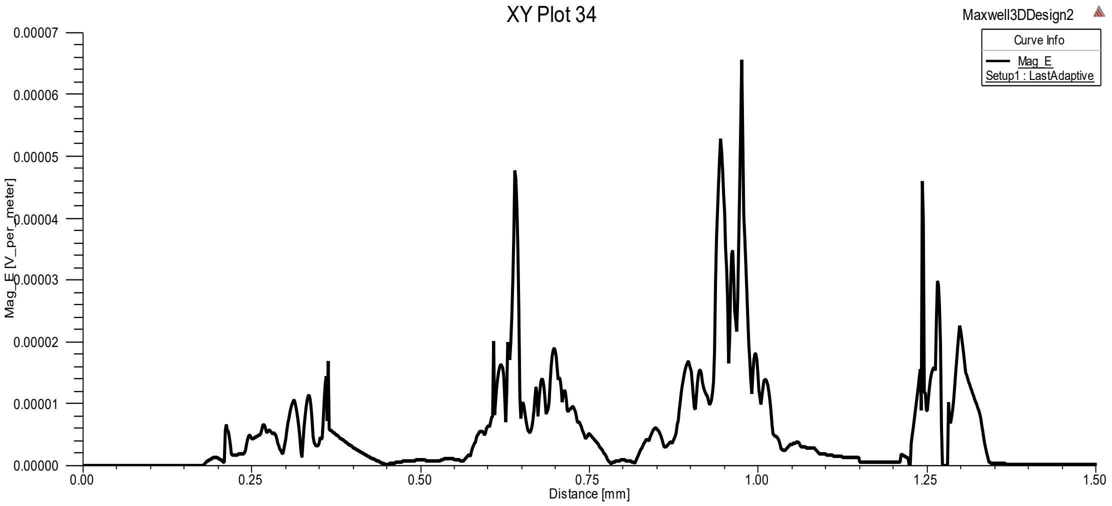


Fig. 18. Polluted insulator electric field distribution graph

6. Conclusions

The utilization of electrical transmission systems has led to the use of a wide range of insulators. These insulators are employed in various geographical regions, including arid regions, coastal areas, and agricultural zones, each facing distinct forms of environmental contamination. Pollution can significantly impact the insulation behavior of insulators, leading to deterioration and compromised resilience. However, the practical implementation of insulators in HVAC conditions has its limitations. Therefore, it is crucial to understand the flashover performance and consider essential parameters when designing and sizing insulators for HVAC environments. Among the insulators, glass exhibits the most significant electric field magnitudes compared to ceramics and plastic. On average, it is 15% higher to withstand the capability of glass insulators compared to plastic and ceramic. This research aims to elucidate the disparities in analyzing different insulators based on their respective materials.

Acknowledgment

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