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Simulation-Based Comparative Analysis of Electric Field Distribution and Flashover Risk in High-Voltage Glass Insulators under Pollution Levels

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ABSTRACT

High-voltage (HV) insulators are essential components in power transmission systems, ensuring electrical insulation and operational reliability. However, their performance is significantly affected by environmental pollution, which leads to surface contamination, non-uniform electric field distribution, and an increased risk of flashover. This study addresses the problem of insulation performance degradation under varying pollution conditions by investigating the relationship between pollution severity, electric field distribution, and flashover risk in a 132 kV transmission line insulator system represented by a single 11 kV glass disc model. The purpose of this research is to evaluate the effect of pollution severity on electric field behaviour and identify critical regions that are susceptible to electrical stress and flashover initiation. A finite element method (FEM)-based numerical simulation was conducted using COMSOL Multiphysics. A two-dimensional axisymmetric model was developed. Pollution conditions were modelled as a surface conductive layer with varying severity levels, representing clean, light, moderate, and heavy contamination. The principal results show that increasing pollution severity significantly distorts the electric field distribution along the creepage distance of the insulator. Electric field intensification is observed at critical regions such as the pin, sheds, and triple junction (air–glass–metal interface). Heavy pollution conditions result in severe field non-uniformity, which increases partial discharge activity and flashover susceptibility. The study concludes that pollution severity has a strong nonlinear influence on electric field distribution and insulation performance in high-voltage systems. The findings highlight the importance of considering environmental contamination in the design, operation, and maintenance of transmission line insulators.

1. Introduction

High-voltage (HV) transmission systems play a vital role in ensuring the continuous and reliable delivery of electrical energy from generation sources to end users. The performance and stability of these systems depend significantly on the integrity of outdoor insulation components, particularly

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transmission line insulators that provide both mechanical support and electrical insulation under high operating voltages [1]. This has been widely emphasized in high-voltage engineering studies focusing on system stability and insulation coordination [2].

Glass suspension insulators are widely used in HV transmission systems due to their high mechanical strength, stable dielectric properties, long service life, and ease of inspection. Their transparent nature allows damaged units to be visually identified during maintenance, making them a practical choice for utility companies. However, as reported in [3], these insulators are highly vulnerable to environmental contamination, particularly in tropical and coastal regions where humidity, industrial emissions, dust, and sea salt are continuously present. In such environments, pollution accumulation on insulator surfaces is accelerated, significantly affecting their electrical performance [3,4].

The impact of surface pollution on insulator performance has been extensively studied. Hampton [3] demonstrated that pollution severity strongly influences flashover voltage under wet conditions. When pollution layers become wet, their conductivity increases, resulting in leakage current formation and surface discharge activity [2,3]. This leads to non-uniform voltage distribution along the creepage path [4].

Pollution also causes electric field distortion along the insulator surface, leading to localized field enhancement near metallic fittings and geometrical discontinuities [4]. These effects contribute significantly to insulation degradation and flashover initiation [4,5].

In order to better understand the electrical behaviour of polluted insulators, numerical simulation techniques such as the Finite Element Method (FEM) have been widely adopted. FEM enables detailed analysis of electric field distribution, voltage stress, and insulation performance under various pollution conditions without requiring extensive experimental setups. Previous research has demonstrated that FEM-based models are effective in capturing electric field variations along polluted insulator surfaces and provide valuable insight into insulation behaviour under real operating conditions [6,7]. Compared to experimental methods, FEM offers greater flexibility in evaluating multiple pollution scenarios while reducing cost and improving repeatability and accuracy [7].

Although significant progress has been made in the study of polluted insulators, most existing research has considered pollution effects, electric field distribution, and flashover behaviour separately. Limited studies have integrated these aspects into a unified FEM framework that compares multiple pollution severity levels for a 132 kV glass suspension insulator. Furthermore, the relationship between electric field intensification and flashover risk under progressively increasing contamination levels remains insufficiently explored, particularly in tropical environmental conditions where humidity and salt deposition are dominant factors. This limitation has also been noted in recent studies focusing on insulation performance in harsh environments [16,17].

Therefore, this study aims to investigate the influence of pollution severity on electric field distribution and flashover risk in a 132 kV transmission line insulator system represented by a single 11 kV glass disc model using the Finite Element Method. The analysis considers clean, light, moderate, and heavy pollution conditions to evaluate variations in electric field intensity and insulation performance. The findings of this study are expected to enhance the understanding of pollution-induced electrical stress mechanisms and provide useful insights for improving insulation design, condition monitoring, and maintenance strategies in high-voltage transmission systems, particularly in tropical and coastal regions [18-20].

2. Methodology

2.1 Model Setup

A Finite Element Method (FEM) simulation was developed using COMSOL Multiphysics to analyse the electric field distribution of a 132 kV transmission line glass suspension insulator system. The study focused on evaluating the electrical stress distribution under varying surface pollution conditions.

A standard glass insulator consisting of metal cap, pin, glass disc, and cement interfaces was modelled. A single 11 kV glass disc as illustrated in Figure 1 was used as a representative unit of the full 132 kV insulator string.

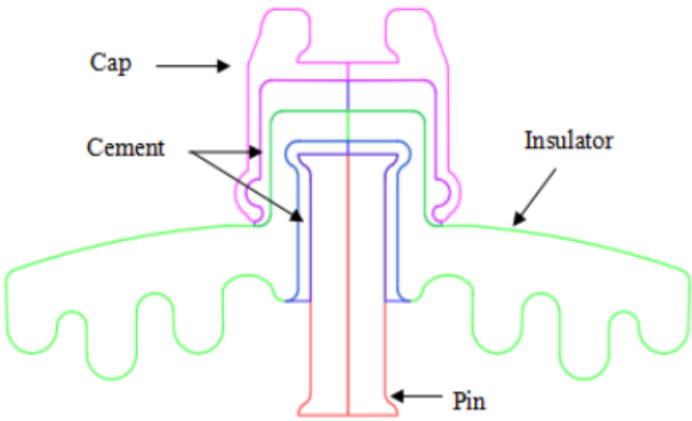

Fig. 1. Glass insulator model

To reduce computational complexity while maintaining physical accuracy, the system was simplified into a two-dimensional axisymmetric electrostatic model, as shown in Figure 2.

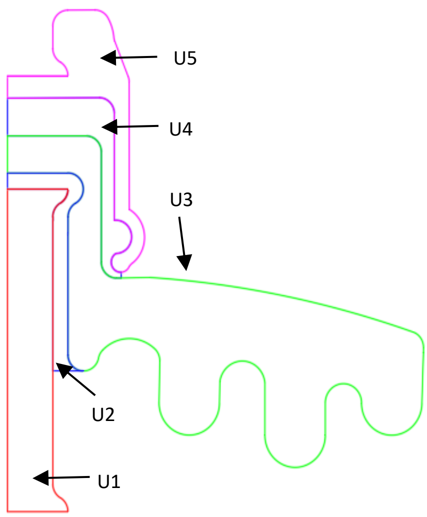

Fig. 2. Glass Insulator in 2D Model

The model comprises multiple material domains, namely the metallic pin (U1), cement interface between pin and glass (U2), glass body (U3), cement interface between glass and cap (U4), and metal cap (U5). Appropriate material properties, including electrical conductivity and permittivity, were assigned to each region based on standard high-voltage insulation parameters. A high-voltage potential was applied at the conductor terminal, while the tower end was grounded to represent actual operating conditions in transmission systems.

2.2 Pollution Modelling

Surface pollution was modelled as a non-uniform conductive layer distributed along the creepage distance of the insulator. This approach allows the simulation of leakage current formation and electric field distortion under contaminated conditions.

Four conditions were considered in this study: clean, light pollution, moderate pollution, and heavy pollution. The pollution severity was represented by varying the surface conductivity along the insulator profile, which directly affects the electric field distribution and leakage current behaviour. Figure 3 illustrates the conceptual representation of the pollution layer applied in the simulation.

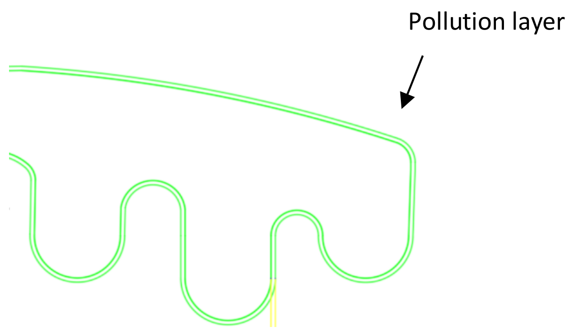

Fig. 3. Glass insulator surface with pollution layer

This modelling approach is widely used in FEM-based insulation studies as it effectively captures the transition from dry non-conductive conditions to wet conductive behaviour under environmental exposure.

2.3 Electric Field Distribution Analysis

The electric field distribution was computed along the creepage distance of the insulator surface under all pollution conditions. The analysis focused on identifying high-stress regions, particularly at the pin junction, shed edges, and triple junction regions (air–glass–metal interfaces), where electric field enhancement is typically observed.

These regions are known to be critical locations for partial discharge initiation and flashover development. For each pollution case, the maximum electric field intensity was extracted and used for comparative evaluation to quantify the effect of pollution severity on insulation performance.

2.4 Regression Analysis

The relationship between pollution severity and electric field intensity was modelled using a second-order polynomial regression, as expressed in Eq. (1).

$$E(x) = ax^2 + bx + c \tag{1}$$

where x represents pollution severity (pollution thickness), E(x) represents electric field intensity, and a, b, and c are regression coefficients obtained from simulation results.

This regression model is used to capture the nonlinear relationship between surface contamination and electrical stress distribution along the insulator surface.

2.5 Flashover Risk Evaluation

Flashover risk was evaluated based on the maximum electric field intensity at critical regions identified in the simulation. A threshold-based criterion was used to estimate the likelihood of flashover initiation under different pollution conditions.

A comparative trend analysis was conducted to investigate the relationship between pollution severity and flashover risk. The results indicate that increasing pollution severity leads to higher surface conductivity, which intensifies electric field concentration and increases the probability of flashover occurrence in high-voltage insulators.

3. Results
3.1 Electric Field Distribution Analysis

The analysis was conducted under light, moderate, and heavy pollution conditions for a 132 kV system represented by a single 11 kV disc model. The electric field distribution along the creepage distance under different pollution conditions is presented in Figure 4.

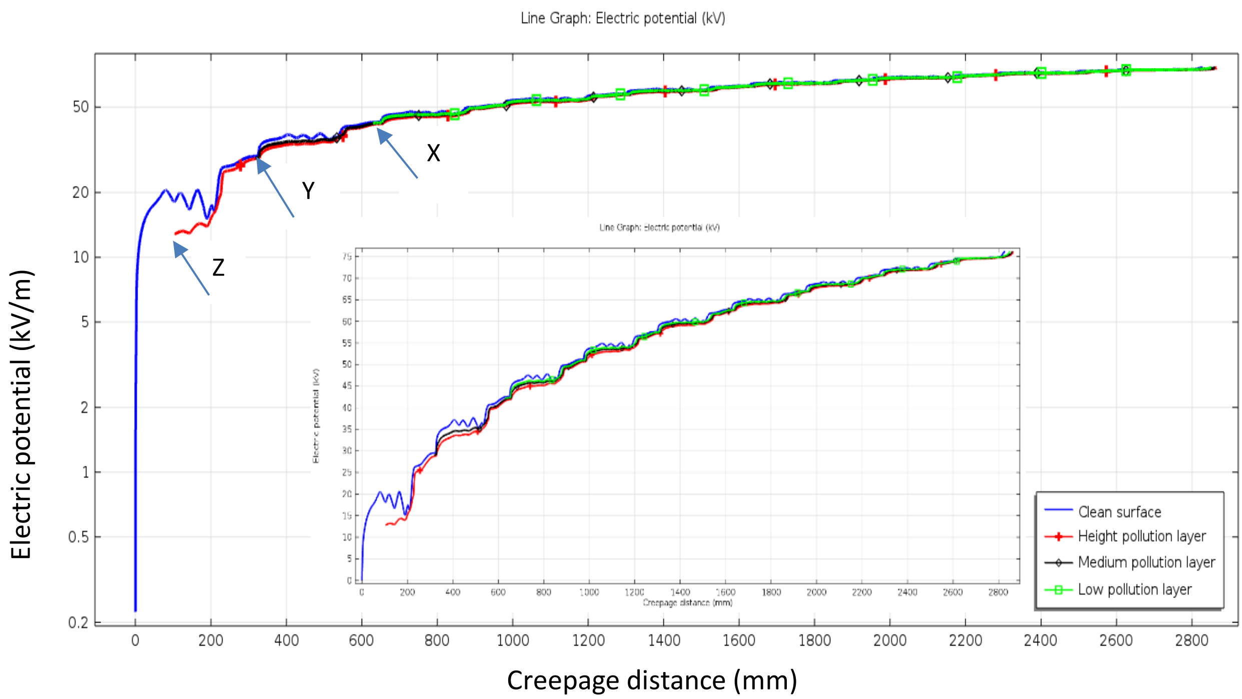

Fig. 4. Electric field distribution along creepage distance of 11 kV glass insulator under different pollution severity levels

Under light (low) pollution conditions, the electric field distribution remains relatively uniform along the insulator surface, with only minor field concentration observed near metallic fittings. This indicates minimal influence of surface conductivity and stable insulation behaviour.

As the pollution level increases to moderate (medium) conditions, noticeable distortion of the electric field begins to occur. Increased surface conductivity results in localized electric field enhancement, particularly near the pin and cap regions. This indicates the onset of insulation stress due to contamination along the creepage path.

Under heavy (height) pollution conditions, severe electric field intensification is observed. The field distribution becomes highly non-uniform, with strong concentration at geometrical discontinuities and triple junction regions (air–glass–metal interfaces). These regions are identified as critical locations for partial discharge initiation under high-voltage operation.

3.2 Regression Analysis of Electric Field Behaviour

The variation of electric field intensity with respect to pollution severity is shown in Figure 5.

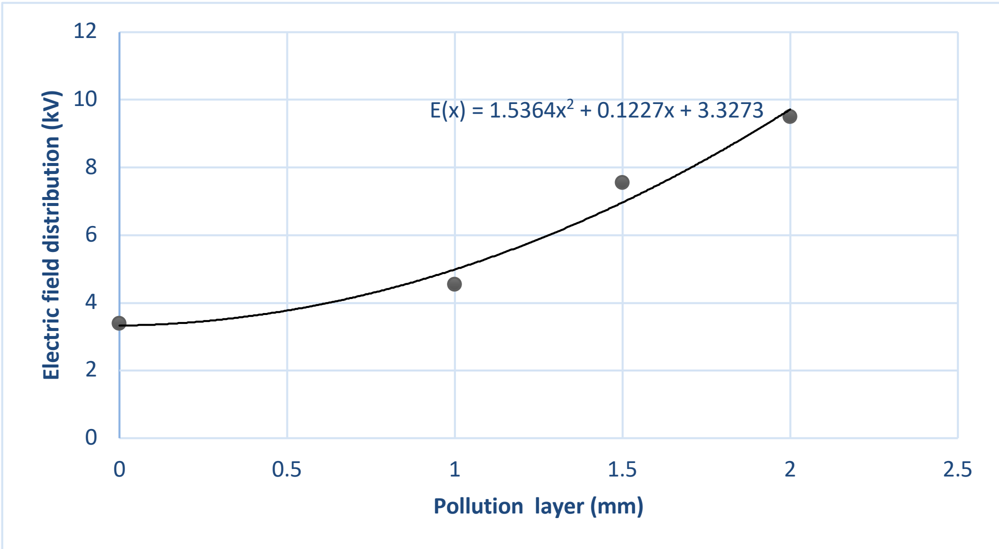

Fig. 5. Regression model of electric field vs pollution thickness

The results indicate that the relationship between pollution severity and electric field intensity is nonlinear. The relationship is expressed using a second-order polynomial regression model as given in Eq. (2).

$$E(x) = 1.5364x^2 + 0.1227x + 3.3273 \tag{2}$$

The regression model shows that electric field intensity increases at an accelerating rate as pollution severity increases. The quadratic term dominates the behaviour, indicating strong nonlinearity in the system response.

Physically, this behaviour is attributed to the formation of conductive pollution layers on the insulator surface, which alter boundary conditions and increase electric field distortion along the creepage distance.

3.3 Flashover Risk Evaluation

Flashover risk is assessed based on the electric field distribution at critical regions of the insulator surface. The results indicate that higher pollution severity leads to increased electric field concentration at triple junction regions.

The increase in surface conductivity under polluted conditions enhances electric field distortion, reducing the dielectric strength of the insulator and increasing susceptibility to partial discharge initiation and flashover occurrence.

4. Conclusions

This study investigated the effect of pollution severity on electric field distribution and flashover risk in a 132 kV transmission line insulator system represented by a single 11 kV glass disc model using a Finite Element Method (FEM) approach. The primary objective of this study was to evaluate the relationship between pollution severity, electric field intensification, and flashover risk.

The results obtained from the simulation clearly demonstrate that increasing pollution severity significantly distorts the electric field distribution along the creepage distance of the insulator. This leads to higher localized electrical stress, particularly at geometrical discontinuities and triple junction regions.

A nonlinear relationship between pollution severity and electric field intensity was observed, indicating that electric field enhancement increases at an accelerating rate as contamination levels rise. This behaviour confirms that the insulation system becomes more vulnerable under higher pollution conditions, where critical field intensification occurs at regions most susceptible to partial discharge and flashover initiation.

Overall, the findings of this study successfully respond to the research objective by confirming the direct relationship between pollution severity, electric field distortion, and flashover risk. These results emphasize the importance of considering environmental contamination in the design, operation, and maintenance of high-voltage insulator systems.

Although the present study is based on numerical simulation, the results are consistent with established literature, supporting the validity of the FEM model. Future work is recommended to include experimental validation and multiphysics coupling, such as thermal and moisture effects, to further enhance model accuracy under real operating conditions.

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