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Impact of ESDD-Standardised Pollution on Partial Discharge Inception and AC Breakdown Voltage of 11 kV Disc Insulators

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ABSTRACT

Outdoor porcelain insulators are significant in power distribution due to the fact that they offer insulation and mechanical support to overhead lines. Some of the environmental contaminants that may cause impairment of performance, especially under AC stress, are dust, salt, and moisture. The existence of moisture on the insulator surface can lead to the formation of soluble salts, creating a conductive layer that leads to increased leakage current, dry-band formation, and a reduction in flashover voltage. This experiment was designed to investigate the influence of the severity of pollution upon the AC breakdown voltage of 11 kV porcelain disc insulators based on the standard Equivalent Salt Deposition Density (ESDD). The conditions were controlled to simulate dry and wet states of clean, light, medium, and heavy pollution, as stipulated in IEC 60507. Besides, COMSOL Multiphysics, through the finite element simulation function, was used to imitate the electric field density and the leakage current for each level of pollution. The results showed that the breakdown voltage decreased with an increase in pollution, and the most meaningful outcome was that of wet conditions. It is also found through simulations that, in the case of heavy pollution, the strengthening of the electric field around the high-voltage electrodes becomes higher. The agreement between the experiment and simulation supports the modelling strategy and validates that the hybrid techniques are trustworthy in identifying the performance of the insulator in a polluted environment.

Keywords: Porcelain insulator; AC breakdown voltage; Pollution severity; ESDD; Electric field distribution.

Nomenclature (Greek symbols towards the end)

°C	Degree Celsius
σ_θ	Electrical conductivity at temperature θ
σ_{20}	Volume conductivity at 20°C

Abbreviations

AC	Alternating Current
DC	Direct Current
ESDD	Equivalent Salt Deposit Density
FEA	Finite element analysis
Hz	Hertz
kV	kilovolt
L	Liter
NaCl	Sodium chloride

1.0 INTRODUCTION

The insulators play a significant part in electrical power networks and are used to maintain a safe distance between energised conductors and grounded support structures by offering electrical insulation as well as mechanical support. Among others, porcelain insulators continue to dominate transmission and distribution systems because they are very strong mechanically, thermally stable, and have a long life. Nevertheless, when these insulators are put in the open air, they are regularly subject to external environmental contamination of dust, factory emissions, and sea salts. Over time, the presence of these contaminants on the surface of the insulators limits the insulation capacity, and the system becomes more susceptible to electrical failures.

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The presence of moisture in the form of rain, fog, or surrounding humidity in a polluted environment causes soluble salts, which are deposited on the insulator surface, to create a conductive layer. This layer permits leakage currents to circulate through the surface, and local heating is caused as a result of resistive loss. Furthermore, due to uneven evaporation of moisture, dry bands are deposited along the path of leakage, and the effect is translated to an inhomogeneous distribution of the electric field. This applied voltage is subsequently focused on these dry bands, resulting in partial discharges and localised arc formation. As the degree of voltage stress escalates, these arcs could increase in length on the insulator surface and eventually bridge the entire leakage distance to cause flashover. In short, this is a surface breakdown event that may lead to the failure of systems and destruction of power system equipment [1-2].

Earlier works have determined that the degree of pollution is a powerful predictor of the insulator flashover. The impact of contamination is normally measured in terms of the Equivalent Salt Deposit Density (ESDD), which is the quantity of soluble salt on the insulator surface. Most studies have documented that flashover voltage is inversely proportional to ESDD, and it is generally a response to a negative power-law dependency between them [3]. Although these studies give a good understanding of the effects of pollution, much of the research exclusively concentrated on overall performance patterns, DC experimental circumstances, or unstandardised levels of contamination. Although several studies have investigated AC flashover under polluted conditions, most focus either on experimental flashover behaviour or numerical modelling independently. A systematic experimental-numerical correlation under strictly IEC 60507 ESDD-standardized conditions, particularly incorporating PDIV and breakdown voltage trends for 11 kV porcelain disc insulators, remains limited.

The phenomena of AC breakdown are important to be understood, as a majority of power systems work on the basis of alternating current, in which the periodic switching of the electric field polarity of the current has a substantial impact on leakage current characteristics, discharge activity, and arc formation. In contrast to DC stress, AC voltage provides dynamic processes of charge and discharge of surfaces, which have a direct influence on the process of arc initiation and propagation. Hence, the use of DC or generalised flashover data may lead to an incorrect evaluation of the insulating performance in the existing operating circumstances [4].

Furthermore, despite the vast application of numerical modelling techniques in the study of the distribution of the electric field in high-voltage insulation equipment by using finite element analysis (FEA), no research study has been undertaken to present a systematic relationship between experimental data of the AC breakdown voltage and predicted behaviours of the electric field gradient under pollution conditions standardised by ESDD. The absence of such information restricts the applications of simulation tools in the prediction, designing, and assessment of the conditions of polluted insulators.

The paper is meant to assist in overcoming these deficiencies by considering the effect of the degree of pollution on the foundation of the breakdown voltage variation of porcelain disc insulators when they are controlled under predetermined levels of ESDD at the setup levels. Experimentally, the samples of porcelain insulators are tested in order to simulate various conditions of pollution under controlled NaCl solutions. In addition, COMSOL Multiphysics is used to predict the distribution of the electric field along the insulator surface when the conditions of corresponding contamination are being taken into consideration. Through experimental and finite element results, this study not only provides a solid evaluation of how the performance has deteriorated due to pollution but also a better understanding of how ESDD, electric field strengthening, and the nature of AC breakdown are related to one another. The results can be used in developing more credible insulator design, selection, and maintenance plans of power systems used in a polluted environment.

2.0 METHODOLOGY

The general methodology embraced in this research, as indicated in Figure 1, shows a stepwise flow of how data were to be collected, starting with preparing the insulator, its measurements, and finally its validation. The method combines experimental testing and finite element–based numerical evaluation by means of finite element simulation to determine the performance of porcelain insulators under varying pollution conditions. In the experiment, the porcelain insulators were polluted with controlled salt solutions, dried, and subjected to AC breakdown voltage at different levels of pollution. Simultaneously, the relevant electric field distribution was analysed in terms of numerical simulations (COMSOL Multiphysics). The validation of the modelling approach was then done by comparing the experimental and simulation results.

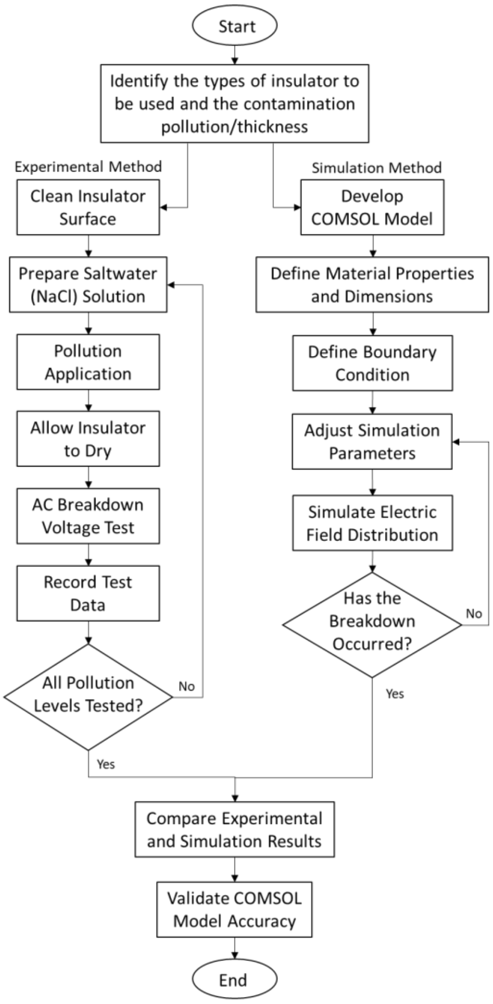


Figure 1. Flowchart of experimental and simulation process

2.1 Pollution preparation

The ESDD on the porcelain insulators was determined through a standardised washing and pollution procedure per IEC 60507 [5]. To avoid contamination, the plastic wrap was originally applied to the cap and pin regions so that only the insulator surface was polluted. A 1000 cm³ of distilled water with a low value of conductivity (less than 0.001 S/m) was then used to wash the surface, and any contaminants removed were then collected and analysed.

Controlled pollution solutions were prepared by dissolving precise quantities of sodium chloride (NaCl) in 1 L of distilled water, as specified by IEC 60507, where NaCl is used as the main contaminant due to its high solubility and standardized dielectric properties in pollution testing [6]. The prepared solutions were sprayed uniformly onto the insulator surface and allowed to dry naturally for 24 hours at room temperature (≈29 °C). This drying duration ensures complete evaporation of moisture and stable crystallisation of salt deposits on the surface before testing, which is consistent with common artificial-pollution preparation practices reported in high-voltage insulation studies and IEC-based procedures [6]. Four pollution conditions, which are clean, light, medium, and heavy, were established, as summarised in Table 1.

Table 1: Pollution Level Classification

Pollution Level	NaCl (g)	Distilled Water (L)	ESDD Range (mg/cm^2)
Clean	0	1	0
Light	10	1	< 0.06
Medium	50	1	0.06 - 0.12
Heavy	100	1	0.12 – 0.24

2.2 ESDD measurement

After drying, the conductivity and temperature of the collected pollution solution were measured. The measured conductivity was corrected to the reference temperature of 20 °C using the IEC 60507 correction method.

$$\sigma_{20} = \sigma_{\theta}[1 - b\,(\theta - 20)] \tag{1}$$

where σ_{20} is the volume conductivity at 20°C, σ_{θ} is the measured conductivity at temperature θ, and b is the temperature correction factor given by:

$$b = -3.200 \times 10^{-8}\theta^{3} + 1.032 \times 10^{-5}\theta^{2} - 8.272 \times 10^{-4}\theta + 3.544 \times 10^{-2} \tag{2}$$

The S_a and ESDD were then calculated using:

$$S_a = (5.7 \times \sigma_{20})^{1.03} \tag{3}$$

$$ESDD = (S_a \times V)/A \tag{4}$$

where V is the volume of distilled water used, and A is the insulator surface area.

2.3 AC breakdown voltage testing

Figure 2 shows the AC breakdown voltage tests that were conducted in a high-voltage laboratory under controlled conditions. The porcelain insulator was suspended inside with sufficient clearance from grounded structures. Next, a 50 Hz AC voltage was applied and increased gradually at a rate of 2 kV/s. This ramp rate was selected to ensure stable voltage application while avoiding excessive thermal stress until flashover occurred. The applied voltage was measured using a capacitor voltage divider connected to a peak voltmeter. For wet condition tests, the insulator surface was uniformly sprayed with a fine mist to simulate fog or light rain. The breakdown procedure was repeated following the same protocol as the dry tests. Between successive tests, sufficient recovery time was allowed to ensure thermal dissipation and surface stabilisation.

For polluted-condition testing, the applied voltage was limited to 90 kV to ensure safety margins and protect the test equipment. However, under clean dry conditions, the voltage was increased until flashover occurred, reaching 100 kV, which is within the rated capability of the high-voltage test system.

(a) (b)

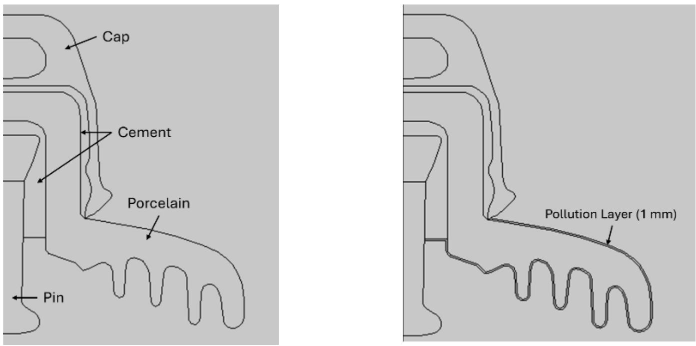
Figure 2. (a) Laboratory experiment setup and (b) Control panel unit

2.4 Modelling of dry and wet pollution conditions

A two-dimensional axisymmetric model of an 11 kV porcelain disc insulator was developed in COMSOL Multiphysics as shown in Figure 3. For dry pollution conditions, a uniform pollution layer with a thickness of 1 mm was applied along the insulator surface, and its conductivity was adjusted according to the experimentally measured ESDD values.

For wet pollution conditions, an additional conductive water film with a thickness of 0.2 mm was modelled on top of the pollution layer to represent moisture-induced dissolution of surface salts, as illustrated in Figure 4. The relative permittivity of the water film was set to 81, while its conductivity was varied to represent clean, light, medium, and heavy pollution conditions. Material properties for all model components are listed in Table 2.

A finite element mesh was generated, and a steady-state solver was used to compute the electric potential and electric field distribution under applied voltage. The Cut Line 2D feature is implemented to extract and quantify the electric field strength along the critical triple-junction region, as illustrated in Figure 5.



(a) (b)

Figure 3. 2D geometry model of 11kV porcelain disc insulator in COMSOL
(a) clean condition, (b) polluted condition

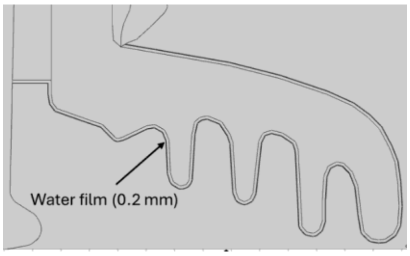


Figure 4. A conductive water film layer on the insulator's pollution surface

Table 2: Material properties for COMSOL simulation [7, 8]

Material	Relative Permittivity (ϵ_r)	Conductivity (S/m)
Air	1	$1\text{x}10^{-20}$
Porcelain	6	$1\text{x}10^{-14}$
Conductors	1	$1.45\text{x}10^{6}$
Cement	2.1	$1\text{x}10^{-14}$

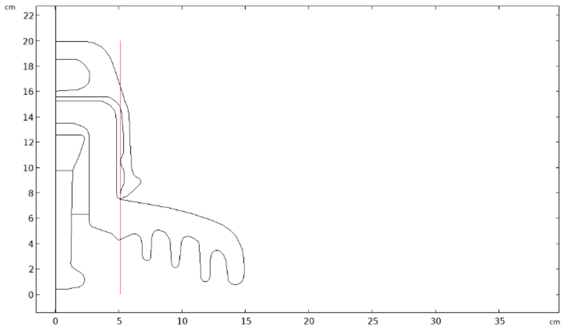


Figure 5. Location of Cut Line 2D used to analyse the electric field in the triple junction region

2.5 Data analysis and validation

Experimental flashover voltage results were averaged across repeated tests for each pollution level. Outliers exceeding ±10% deviation from the mean were excluded to minimise random experimental variations. From the simulation results, the electric field distribution along the insulator surface was extracted, with particular attention given to regions near the high-voltage electrode where field intensification is expected. Validation was performed by comparing the experimental flashover voltage trends with the simulated electric field enhancement under corresponding pollution conditions. Although the simulation does not directly predict flashover voltage, consistent trends observed between the experimental and numerical results confirm the reliability of the proposed modelling approach.

3.0 RESULTS AND DISCUSSION

This section presents and discusses the experimental and numerical results obtained for an 11 kV porcelain disc insulator subjected to different pollution severities. Experimental measurements of ESDD, partial discharge inception, and AC breakdown voltage are first analysed under dry and wet conditions. The discussion then integrates finite element simulation results to interpret electric field distribution and leakage current behaviour, followed by an experimental–numerical validation.

3.1 Experimental results

3.1.1 ESDD characterisation

The measured conductivity and ESDD values for clean, light, medium, and heavy pollution levels are summarised in Table 3. The results confirm that the applied contamination procedure reliably reproduced the pollution severity classes defined in IEC 60507. Conductivity and ESDD increased monotonically with the amount of deposited NaCl, demonstrating a direct relationship between surface contamination and electrical conductivity. The progressive increase in surface contamination with pollution severity is visually evident in Figure 6, supporting the measured increase in ESDD values and confirming the repeatability of the pollution preparation process [9].

Table 3: Measured ESDD and conductivity of polluted insulators

Pollution Severity	NaCl (g)	Conductivity at 20°C (S/m)	ESDD (mg/cm^2)	IEC 60507 Classification
Clean	0	0.00013	0.00038	0
Light	10	0.0122	0.041	< 0.06
Medium	50	0.025	0.085	0.06 - 0.12
Heavy	100	0.074	0.232	0.12 – 0.24


(a) (b) (c)

Figure 6. Pollution severity (a) light (b) medium (c) heavy

3.1.2 AC breakdown voltage in dry and wet conditions

Table 4 presents the measured partial discharge inception voltages (PDIV) and AC breakdown voltages under dry and wet conditions for all pollution levels. The breakdown voltage in dry conditions also varied proportionately with an increasing level of pollution, where 100 kV of a clean insulator was reduced to 80 kV with heavy pollution, representing a 20% reduction. Such a small decrease indicates that surface contamination, in dry conditions, is not sufficient to establish a continuous conductive path that will render the dielectric strength of the insulator to decrease drastically.

On the contrary, an increasing degree of reduction in the partial discharge inception voltage was recorded as the pollution increased, even in dry conditions. This proves that surface contaminants give rise to the local intensification of the electric stress and reduce the effective range of creepage that would initiate early discharge before full flashover. The representative flashover events under dry conditions are demonstrated in Figure 7, with local arcs occurring around the metal fittings that coincide with the higher values of breakdown voltages under dry polluted conditions.

The impact of the degree of pollution significantly increased under wet conditions. The breakdown voltage consistently decreased from 85 kV in the case of the clean insulator to 63 kV in the case of heavy pollution, representing a 25.9% reduction. The presence of moisture dissolves the deposited salts, presenting a conductive film on the surface, favouring the flow of leakage currents and dry-band formation, causing the ignition at much lower voltage values (flashover). The partial discharge inception voltage declines dramatically with pollution severity [10]. In simpler terms, wet contamination provides rather favourable conditions for discharge activity. For wet conditions, the corresponding flashover behaviour is shown in Figure 8, where continuous surface arcs propagate along the whole creepage path with heavy pollution.

Table 4: AC breakdown voltage in dry and wet conditions

Pollution Severity	Dry Conditions		Wet Conditions	
	Partial Discharge Inception Voltage	AC Breakdown Voltage	Partial Discharge Inception Voltage	AC Breakdown Voltage
Clean	53 kV	100 kV	42 kV	85 kV
Light	46 kV	90 kV	30 kV	75.3 kV
Medium	34 kV	87 kV	20 kV	73 kV
Heavy	30 kV	80 kV	11 kV	63 kV

(a) (b) (c)

Figure 7. AC breakdown voltage (dry condition)
(a) light pollution, (b) medium pollution, and (c) heavy pollution

(a) (b) (c)

Figure 8. AC breakdown voltage (wet condition)
(a) light pollution, (b) medium pollution, and (c) heavy pollution

Figure 9 summarises the relation of AC breakdown voltage and ESDD under dry and wet conditions. For a given pollution level, the breakdown voltage under wet conditions is always less than the breakdown voltage obtained under dry conditions, illustrating the predominant role of moisture in the activation of surface contamination and the acceleration of flashover occurrence [11].

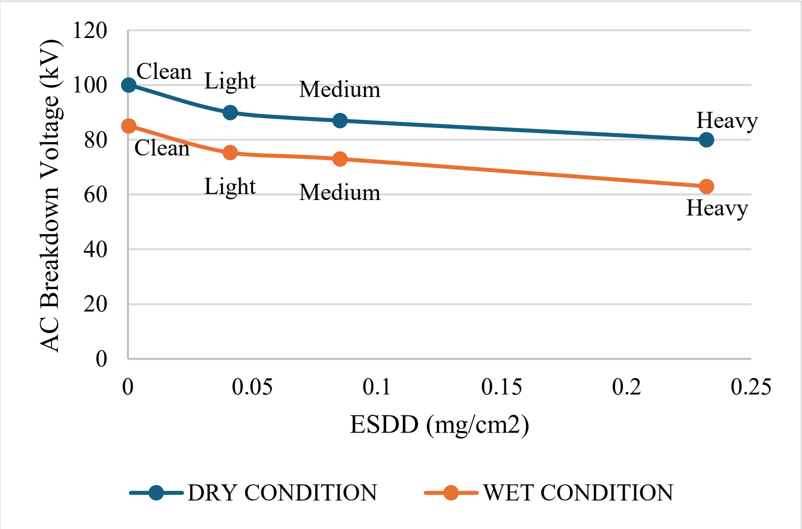


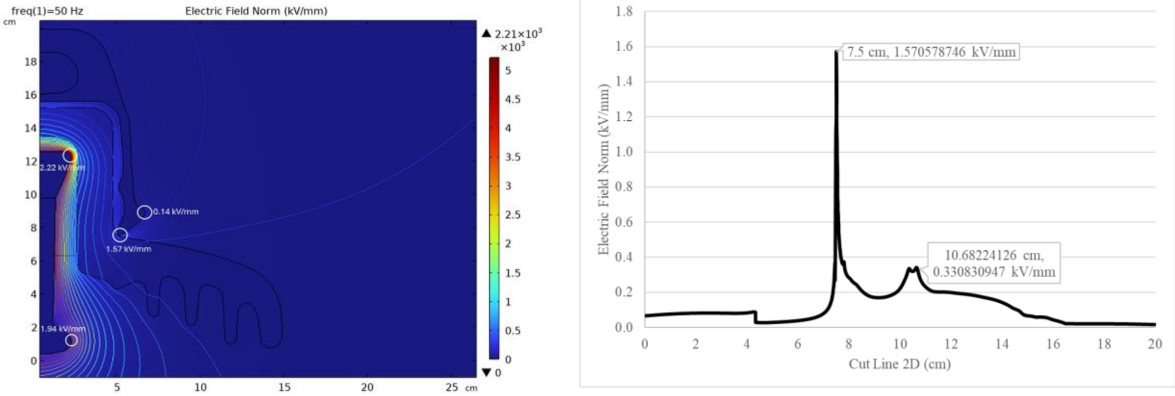
Figure 9. Relationship between AC breakdown voltage (kV) and ESDD (mg/cm^2) under dry and wet conditions

3.2 Simulation results

3.2.1 Clean insulator under normal operating conditions

A clean and dry 11 kV porcelain disc insulator is mainly controlled by the geometry and the permittivity of the material. Figure 10 shows that the maximum electric field was found at the triple-junction points around the high-voltage electrode, where the conductor, porcelain, and the air between them intersected. The electric field was also non-uniform along the triple-junction region, and there were localised peaks near the high-voltage and ground electrodes, which are potential sites for partial discharge origin under high-stress situations.

The leakage current under normal operating conditions is mostly capacitive in nature, and the phase angle tends to be more than 83°. This behaviour is a characteristic of a clean and dry insulation surface, where surface resistance is high and current flow is controlled by the dielectric properties of the porcelain rather than surface conduction. These results provide a baseline for evaluating the influence of pollution under dry and wet conditions [12, 13].



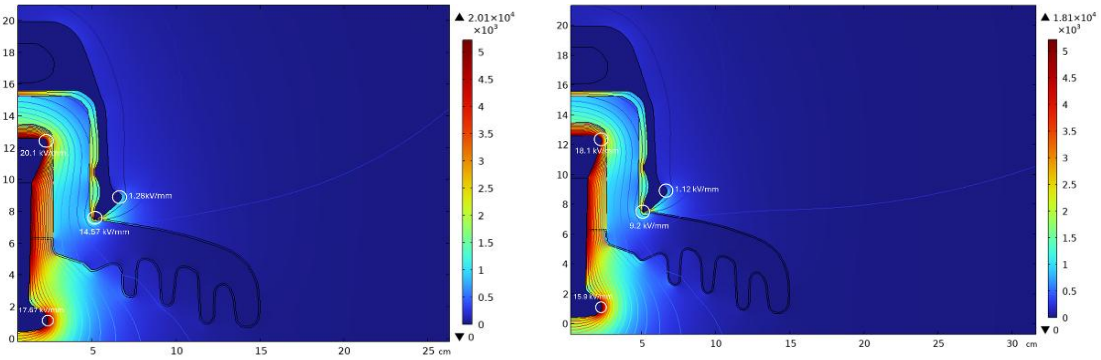
(a) (b)

Figure 10. Electric field distribution (a) contour and (b) x-y plot for a clean insulator in normal conditions

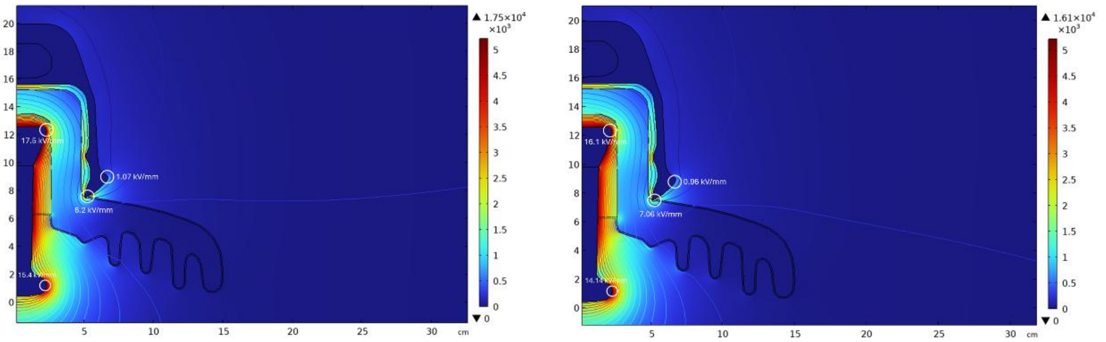
3.2.2 Polluted Insulator Under Dry Conditions

Under dry polluted conditions, the simulated electric field distribution changes systematically with the increase of pollution severity. As shown in Figures 11 and 12, the peak surface electric field decreased progressively by 51.5% from approximately 14.57 kV/mm for the clean insulator to 7.06 kV/mm under heavy pollution. Meanwhile, the applied breakdown voltage also decreased with the increase of ESDD and the reduction in peak electric field was more gradual, indicating that surface conductivity allows partial redistribution of electric charges along the triple-junction points. Although the peak electric field magnitude decreases due to this surface charge redistribution, the conductive pollution layer simultaneously increases leakage current and thermal heating, promoting dry-band formation and facilitating flashover at lower applied voltages.

It is this behaviour that leads to the incidence of flashover under dry contaminated conditions at lower voltages despite lower peak values of the electric field. The weakly conductive contamination layer creates another pathway for surface conduction and, in this way, reduces the extreme local field concentrations at the cost of the facilitated flow of leakage currents. The leakage current analysis, which indicates a smaller phase angle with the increase in the severity of the pollution, supports this interpretation further, given the fact that as the severity of the pollution increases, the possibility of a progressive transformation from the capacitive behaviour to resistive behaviour is experienced. This augmented resistive component heats the surface, leading to the inception of the discharge at lower operating voltages. A quantitative confirmation of this behaviour is clearly shown in Table 5, which indicates an increasing phase angle in the dry condition: a progressive reduction in phase angle with increasing pollution severity, indicating a transition from capacitive-dominated to partially resistive current flow. In agreement with pollution flashover processes described in the literature, this tendency indicates that growing surface conductivity facilitates the process of resistive heating and dry-band initiation [14].



(a) Clean pollution (b) Light pollution



(c) Medium pollution (d) Heavy pollution

Figure 11. Electric field distribution along the insulator surface for varying pollution levels for dry conditions

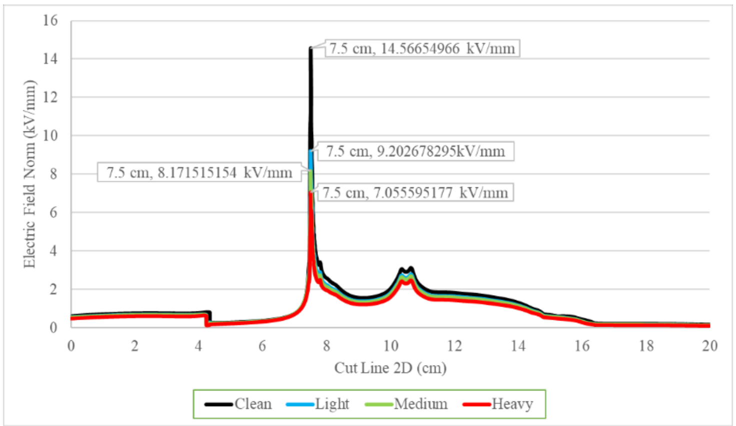


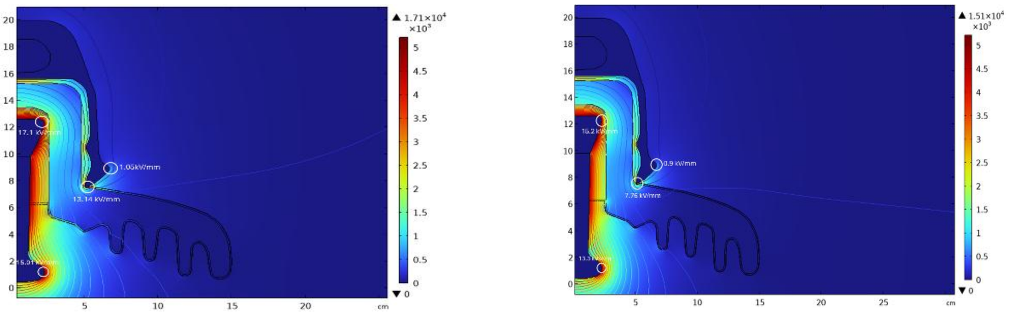
Figure 12. Electric field distribution for all pollution severities under dry conditions

Table 5: Leakage current under dry polluted conditions

Pollution Severity	Applied Voltage (kV)	Peak Voltage (kV)	Complex Values (µA)	Leakage Current (µA)
Clean	100	81.6	579.17 + j689.32	900.33∠50.0°
Light	90	73.5	612.30 + j493.08	786.15∠38.8°
Medium	87	71.0	735.58 + j380.82	828.31∠27.4°
Heavy	80	65.3	742.21 + j353.36	822.03∠25.5°

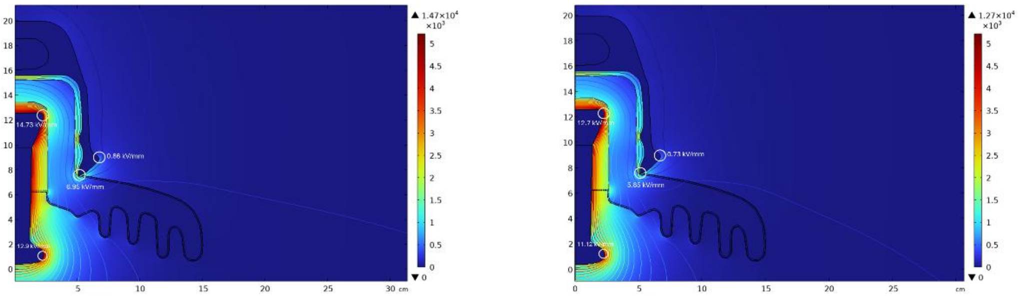
3.2.3 Polluted Insulator Under Wet Conditions

One of the major factors affecting the electrical behaviour of contaminated insulators is moisture. The electric field distributions simulated in the wet condition, as in Figures 13 and 14, showed that there was a significant redistribution of electric stress along the creepage path with the extent of pollution. The maximum value of the surface electric field was lower by about 13.14 kV/mm and 5.85 kV/mm, respectively, for the clean insulator and during heavy pollution, which corresponds to 55.5% reduction from the breakdown voltage observed in the experiments. Such behaviour has been observed in both experimental and numerical studies, indicating that wet pollution enhances the conductivity of the surface and alters the distribution of electric fields, which contributes to the concentration of stress and flashover [15].



(a) Clean pollution

(b) Light pollution



(c) Medium pollution

(d) Heavy pollution

Figure 13. Electric field distribution along the insulator surface for varying pollution levels for wet conditions

In spite of the lower peak electric field, flashover was initiated at much lower voltages as a result of the formation of a highly conductive surface film. Leakage current magnitude strongly increases with pollution severity and the reduction of the phase angle from ~50° to <30° (high shift towards resistive current behaviour). This resistive current causes localised heating, evaporation of the film of moisture, and dry-band formation. The resulting areas of high impedance led to localised electric field intensification, leading to partial discharges and surface arc propagation. These results validate the findings that under wet polluted conditions, flashover is controlled by conduction and dry-band mechanism on the surface of the structure more than by the magnitude of the electric field only. The corresponding increase in the magnitude of the leakage current, the significant decrease of the phase angle and the increase in the severity of pollution, as summarised in Table 6, are further proofs of the predominant role of resistive surface conduction and thermal effects in triggering dry-band formation and surface flashover. This behaviour is in agreement with established observations on wet polluted insulators, whereby moisture-activated surface conduction is dominant in the flashover process [15, 16].

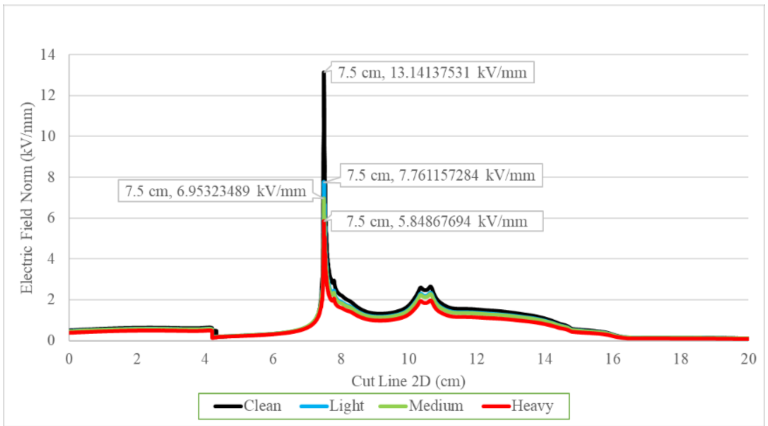


Figure 14. Electric field distribution for all pollution severities under wet conditions

Table 6: Leakage current under wet polluted conditions

Pollution Severity	Applied Voltage (kV)	Peak Voltage (kV)	Complex Values (µA)	Leakage Current (µA)
Clean	85	69.4	413.69 + j452.07	612.79∠47.5°
Light	75.3	61.5	562.21 + j325.37	649.57∠30.1°
Medium	73	59.6	538.09 + j309.54	620.77∠30.0°
Heavy	63	51.4	510.36 + j276.60	580.50∠28.5°

3.2.4 Experiment – Simulation Validation

A comparison of the experimental breakdown voltages with the simulation peak electric field values is given in Table 7. The quantities decline with the increase in the severity of pollution, both under dry and wet conditions, as has been shown in pollution flashover studies where increasing pollutant (salt deposit) levels on porcelain insulators leads to reduced flashover/breakdown voltages due to enhanced surface conductivity and leakage current pathways [14]. For a fixed geometry of the insulator, such a proportionality is to be expected because the electric field for electrostatic simulations with the FEM procedure is proportional to the applied potential [17]. Unlike the DC testing conditions, the investigation on AC testing conditions underlines the dynamic impacts of alternating electric field reversal on the leakage current behaviour and surface discharge formation and development [18].

Table 7: Comparison of simulated electric field and experimental breakdown voltage

Pollution Severity	Dry Conditions		Wet Conditions	
	Experiment Breakdown Voltage (kV)	Peak Electric Field (kV/mm)	Experiment Breakdown Voltage (kV)	Peak Electric Field (kV/mm)
Clean	100	14.57	85	13.14
Light	90	9.2	75.3	7.76
Medium	87	8.2	73	6.95
Heavy	80	7.06	63	5.85

Under dry conditions, the peak electric field reduction follows the experimentally measured breakdown voltage reduction. In contrast, under wet conditions, the correlation is even more marked, reflecting the dominant influence of surface conductivity on electric field distribution and flashover behaviour. The good agreement and complementarity of the numerical predictions and experimental observations are an indication of the correctness of the finite element model with regard to the relative significance of the physical processes governing degradation of insulation by pollution. Similar to previous numerical investigations [3], the simulation does not directly predict, primarily, the flashover voltage, but rather it gives meaningful information on the electric field intensification in polluted conditions. On the whole, the findings demonstrate that FEM simulations, corroborated by the use of experimental evidence, offer a sound means of the analysis and estimation of the performance of a porcelain insulator when subjected to polluted conditions.

4.0 CONCLUSION

Environmental pollution reduces the AC breakdown voltage of 11 kV porcelain disc insulators to a large extent. Experiments and simulations prove that the heavier the contamination, the lower the flashover voltage, with wet conditions having the greatest effect, due to moisture-activated surface conductivity that increases the leakage currents, dry-band formation, and partial discharges. Even the dry condition creates moderate levels of degradation, leading to the importance of emphasising the moisture factor on flashover. These results show the importance of consideration in the design, maintenance, and reliability tests for the insulators regarding contamination in the environment. Future work might take into account mixed pollutants, long-term ageing, higher voltages and better simulations, including the dynamic surface conductivity and thermal effects.

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AUTHORS CONTRIBUTION

Irdina Adriana Ibrahim: Data curation, Formal analysis, Investigation, Methodology, Writing –Original Draft.
Nordiana Azlin Othman: Supervision, Conceptualisation, Validation, Writing –Review & Editing.
Md Aris Nor Asyidi Md Nadzir: Data curation, Formal analysis.

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] C. U. Maheswari, R. V. Maheswari and B. Vigneshwaran, "Impact of Pollution on the Performance of High-Voltage Insulators under Alternating Current," 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), Kanyakumari, India, pp. 76-81, 2025, doi: 10.1109/ICTMIM65579.2025.10988098.

[2] A. A. Salem, R. Abd Rahman, and S. Al-Ameri, "Pollution Flashover Characteristics of High-Voltage Outdoor Insulators: Analytical Study," Arab J Sci Eng, vol. 47, no. 3, pp. 2711–2729, 2022, doi: 10.1007/s13369-021-05745-x.

[3] B. Bolou-Sobai, D. Ayebagbalinyo, and C. Idongha, "Predicting flashover voltage on polluted porcelain insulator," International Journal of Engine Research, vol. 11, pp. 32–37, 2025.

[4] F. Akin, O. Arıkan, and C. C. Uydur, "Investigation of AC and DC breakdown behavior on different solid insulating materials," in Proceedings of the 13th International Conference on Electrical and Electronics Engineering (ELECO), IEEE, 2021.

[5] W. V. R. Suzuki, "Annex A: Measurement of ESDD and NSDD," CIGRE Technical Brochure 36-WG11/Milan/102, 2001.

[6] IEC 60507, Artificial Pollution Tests on High-Voltage Ceramic and Glass Insulators to be Used on AC Systems. IEC: Geneva, Switzerland, 2013.

[7] Krzma, A.S., Khamaira, M.Y. and Abdulsamad, M., 2018, September. Comparative analysis of electric field and potential distributions over porcelain and glass insulators using finite element method. In Proceeding Book of First Conference for Engineering Sciences and Technology (CEST-2018)(Part 2).

[8] Negara, I.M.Y., Asfani, D., Hernanda, I.S., Fahmi, D., Ksatria, A. and Hutabarat, A.K.S., 2023. Investigation of Insulator Performance Under Artificial Contaminants. International Journal of Integrated Engineering, 15(4), pp. 271-280.

[9] Salem, A.A., Al-Gailani, S.A., Amer, A.A.G., Alsharef, M., Bajaj, M., Zaitsev, I., Ngah, R. and Ghoneim, S.S., 2024. Classification of RTV-coated porcelain insulator condition under different profiles and levels of pollution. Scientific Reports, 14(1), p. 22759.

[10] Boudissa, R., Bayadi, A. and Baersch, R., 2013. Effect of pollution distribution class on insulators flashover under AC voltage. Electric power systems research, 104, pp. 176-182.

[11] Khatoon, S., Khan, A. A., Tariq, M., Alamri, B., & Mihet-Popa, L. (2022). Flashover Voltage Prediction Models under Agricultural and Biological Contaminant Conditions on Insulators. Energies, 15(4), 1297. doi:10.3390/en15041297.

[12] Salem, A.A., Abd-Rahman, R., Al-Gailani, S.A., Kamarudin, M.S., Ahmad, H. and Salam, Z., 2020. The leakage current components as a diagnostic tool to estimate contamination level on high voltage insulators. IEEE Access, 8, pp. 92514-92528.

[13] Salem, A.A., Lau, K.Y., Rahiman, W. et al. Leakage current characteristics in estimating insulator reliability: Experimental investigation and analysis. Sci Rep 12, 14974 (2022). doi:10.1038/s41598-022-17792-x.

[14] Salem, A.A., Lau, K.Y., Abdul-Malek, Z., Al-Gailani, S.A. and Tan, C.W., 2022. Flashover voltage of porcelain insulator under various pollution distributions: Experiment and modeling. Electric Power Systems Research, 208, p. 107867.

[15] Huang, P., Liao, Y., Fang, L., Zou, X., Liu, Z., Tian, L. and Zhang, Y., 2025. Electric field distribution analysis of polluted composite insulators based on COMSOL. AIP Advances, 15(8).

[16] Li, X., Liu, Y. and Wang, J., 2025. Influence of surface contamination on electric field distribution of insulators. Chinese Physics B, 34(3), p. 034101.

[17] Belhouchet, K., Ghadbane, I., Zemmit, A., Ouchen, L. and Zorig, A., 2024. Measurement and evaluation of the flashover voltage on polluted cap and pin insulator: an experimental and theoretical study. Electric Power Systems Research, 236, p. 110979.

[18] Yang, Q., Wang, R., Sima, W., Jiang, C., Lan, X. and Zahn, M., 2012. Electrical circuit flashover model of polluted insulators under AC voltage based on the arc root voltage gradient criterion. Energies, 5(3), pp. 752-769.