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Modeling and Analysis of Surface Contamination in Ceramic and Polymeric Insulators Using Partial Discharge Signal Characteristics

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A B S T R A C T

This study aimed to model and analyze the impact of surface contamination on ceramic and polymeric insulators by characterizing and comparing their partial discharge (PD) signal behavior to support condition-based monitoring and predictive design. An experimental laboratory design was employed to expose medium-voltage ceramic and polymeric insulators to controlled contamination layers prepared with standardized saline and artificial pollutants. PD signals were captured under alternating current stress using an IEC 60270–compliant setup consisting of a high-voltage source, coupling capacitor, and Rogowski coil/high-frequency current transformer sensors. Raw signals underwent wavelet-based denoising to suppress environmental noise and were further analyzed using Fast Fourier Transform (FFT) for spectral features and phase-resolved partial discharge (PRPD) mapping to visualize discharge activity across the AC cycle. Equivalent electrical models of contaminated surfaces were developed to simulate PD inception and growth, and the outputs were validated against laboratory measurements. Ceramic insulators exhibited an abrupt transition from sporadic to high-energy discharges once contamination created a conductive film, reflected by sharp increases in apparent charge and dense PRPD clusters around voltage peaks. Polymeric insulators demonstrated a more gradual rise in PD activity with smaller but persistent pulses distributed across the cycle. FFT analysis revealed dominant low-to-mid frequency peaks intensifying faster in ceramics, while polymeric responses remained broader and less concentrated. The electrical models closely matched experimental PD thresholds and spectral signatures, confirming their ability to predict contamination-driven surface breakdown. Surface contamination strongly influences PD activity, and material type governs the discharge evolution pathway.

Keywords: *Partial discharge; surface contamination; ceramic insulator; polymeric insulator; IEC 60270; wavelet denoising; frequency analysis.*

1. Introduction

The safe and reliable performance of high- and medium-voltage insulation systems has long depended on understanding and controlling surface degradation mechanisms, particularly those linked to partial discharges (PD). When solid insulation is subjected to electrical, thermal, and environmental stressors, localized dielectric breakdown can initiate on or near its surface, leading to gradual erosion, contamination-related tracking, and eventual failure (Montanari et al., 2025). This issue is particularly acute in outdoor components such as ceramic and polymeric insulators where airborne pollutants, humidity, and aging combine to create conductive films that trigger discharge activity (Slama et al., 2021). The detection, modeling, and suppression of PD phenomena are therefore fundamental to extending the service life of power assets and maintaining grid reliability.

In recent years, modeling approaches to PD inception have advanced significantly, giving engineers predictive tools to design and validate insulation systems under real-world operating conditions (Babu & Montanari, 2024; Gardan & Montanari, 2023). Work on epoxy-resin and oil-paper systems shows how cavity geometry, surface field intensification, and environmental factors alter PD inception voltage (PDIV) and apparent charge (Aliyu et al., 2023; Hu et al., 2023). New computational frameworks couple field solutions with defect geometry to quantify localized stress, making it possible to anticipate weak points before failures occur (Bao et al., 2024; Montanari, 2025). Importantly, these methods consider not only the idealized field distribution but also electrode shape and material effects that influence PD starting conditions (Gardan & Montanari, 2023).

Parallel to modeling advances, diagnostic technologies have matured to provide more sensitive and interference-immune detection of PD in complex environments. High-frequency and UHF-based measurements have supplemented the traditional IEC 60270 standard, while signal denoising and spectral analysis improve interpretation in the presence of environmental electrical noise (Nugraha & Efendi, 2022; Wu et al., 2024). Sophisticated anti-interference strategies, including adaptive filters and wavelet transforms, are increasingly embedded into monitoring systems for substations and transmission lines (Wu et al., 2024). This trend supports reliable online surveillance even where strong background noise once masked PD signals.

Polymeric insulation, while attractive for its hydrophobicity and light weight, presents unique challenges for PD assessment. Repetitive and low-energy discharges often occur along its surface under pollution stress and can gradually erode hydrophobic coatings or trigger localized heating (Montanari et al., 2023). Advanced design rules for polymeric insulators attempt to shape field distribution and surface profiles to minimize these events, leveraging accurate PDIV modeling of complex geometries such as rectangular conductors and turn-to-turn windings (Naderiallaf, Degano, & Gerada, 2024; Naderiallaf, Degano, Gerada, et al., 2024). Surface shaping combined with materials that resist water film formation has emerged as a strategy to delay discharge onset (Montanari et al., 2023). At the same time, researchers are showing how field enhancements at edges and fillet radii of rectangular conductors can lower PDIV thresholds in inverter-fed motors and similar apparatus (Naderiallaf, Degano, & Gerada, 2024; Naderiallaf et al., 2022b).

Another active area involves suppression strategies that modify surface or bulk material properties. Techniques such as thin PTFE coatings on oil-paper insulation have been shown to reduce PD activity by altering local electric fields and charge mobility (Li et al., 2023). Hydraulic pressure control is also emerging as an effective parameter in oil-filled systems, with experimental evidence demonstrating that increasing static pressure can inhibit point discharges and reduce surface damage under AC stress (Hu et al., 2023; Hu et al., 2024). Similar physical principles can be adapted to sealed components and pressurized gas systems, including GIS, where partial discharges from defects like suspension protrusions remain a reliability concern (Bao et al., 2024).

Field diagnostics have also benefited from non-electrical indicators of surface degradation. Ultraviolet and optical detection methods track dry band activity and contamination-driven discharges on outdoor insulators, even under adverse weather conditions (Slama et al., 2021; Suhaimi et al., 2022). These optical techniques complement electrical monitoring by providing spatial context and real-time visualization of discharges, while harmonic analysis of emitted light enhances discrimination between healthy and defective surfaces (Suhaimi et al., 2022). For compact devices or PCB-based insulation, alternative sensor geometries—such as plate-bar electrodes—have been proposed to improve local PD detection sensitivity (Mulyana et al., 2023).

A key insight across this body of work is that PD phenomena are highly sensitive to geometric details and environmental exposure. The relationship between cavity size and PDIV in epoxy-based insulators underscores the need to control manufacturing imperfections and surface porosity (Aliyu et al., 2023). Similarly, partial discharges at needle-plate interfaces in transformer oils vary strongly with frequency and voltage waveform, informing both test standards and insulation design for dynamic converter-fed equipment (Liang et al., 2023). Attention to waveform effects is especially relevant for modern inverter-fed systems, where non-sinusoidal voltages alter the inception and repetition of PD activity (Naderiallaf et al., 2022a, 2022b).

Within outdoor transmission and distribution assets, surface pollution remains a critical trigger for PD because contaminants create partially conductive paths that distort the local field and lower breakdown thresholds (Slama et al., 2021). Ceramic insulators, although mechanically robust, can experience sudden transition to intense arcing once contamination becomes wet and continuous, while polymeric alternatives show slower but persistent discharge development as hydrophobicity decays. Modeling and experimental approaches to capture these effects are vital to risk-based maintenance and lifetime prediction (Babu & Montanari, 2024; Montanari et al., 2023). By combining laboratory measurements under controlled contamination with validated field-oriented models, it becomes possible to generate predictive “fingerprints” of PD behavior for different insulator materials and defect types.

Recent efforts also emphasize PD-free design rather than mere monitoring. Strategies range from optimizing energization procedures for high-voltage DC cables (Montanari et al., 2025) to refining insulation system layering and laminated busbar configurations to avoid inception-prone zones (Montanari & Cambareri, 2024). For rotating machines, new design rules integrate PDIV predictions into conductor shape and insulation thickness selection (Montanari, 2025; Naderiallaf, Degano, Gerada, et al., 2024). In static assets, field grading and improved electrode geometry continue to play major roles (Gardan & Montanari, 2023). The goal is to build components inherently resistant to discharge rather than relying solely on detection after installation.

This study builds on these developments by focusing on surface contamination modeling and PD signal analysis for ceramic and polymeric insulators used in medium-voltage networks. By applying controlled pollution layers and recording discharges under standardized electrical stress, the work aims to capture the distinct time-domain, frequency-domain, and phase-resolved signatures associated with each material and contamination state. Advanced signal processing, including wavelet denoising and FFT analysis (Nugraha & Efendi, 2022; Wu et al., 2024), is used to isolate true discharge activity from environmental interference and extract reliable diagnostic parameters. The resulting data not only support better understanding of degradation processes but also validate equivalent electrical models that replicate surface conduction under pollution (Babu & Montanari, 2024). Such models can be integrated into predictive maintenance frameworks and PD-free design practices (Montanari & Cambareri, 2024; Montanari et al., 2025).

Ultimately, advancing from raw measurement to robust modeling and material-informed mitigation closes a critical loop in high-voltage asset management. Incorporating both detection and prevention perspectives—as championed by emerging research on optimized energization (Montanari et al., 2025), surface shaping (Montanari et al., 2023), waveform adaptation (Naderiallaf et al., 2022a), and protective coatings (Li et al., 2023)—helps define a new generation of insulators and insulation systems. These efforts enable engineers not only to detect but to anticipate and suppress surface discharge activity in harsh outdoor environments, thereby improving safety, reliability, and long-term cost efficiency in electric power transmission and distribution networks.

2. Methods and Materials

This research used an experimental laboratory design to model and analyze surface pollution on medium-voltage insulators and examine the resulting partial discharge (PD) signals. Two main categories of insulators—ceramic and polymeric (silicone rubber)—were selected because of their widespread use in medium-voltage overhead distribution networks and their differing surface contamination and aging characteristics.

Test samples included both new and artificially aged insulators to replicate realistic service conditions. Surface contamination layers, created with saline solution and artificial pollutants, were applied under controlled laboratory conditions to simulate environmental stressors such as moisture, dust, and salts that typically lead to surface discharge activity. The insulators were energized with a medium-voltage AC supply to reproduce field-relevant electric stress.

The number of samples was chosen to allow comparative analysis between the two insulator types. Tests continued until repeatable discharge patterns were obtained under each contamination severity level.

Partial Discharge Measurement Setup

All PD signals were measured using electrical detection methods standardized by IEC 60270 to ensure comparability and reproducibility. The measurement circuit included:

- **High-voltage source** adjustable up to the rated level of the tested insulators.
- **Coupling capacitor** and **measuring impedance** for capturing PD pulses (capacitive direct method).
- **Rogowski coil or high-frequency current transformer (HFCT)** sensors when indirect coupling was needed.
- **Oscilloscope and digital acquisition system** connected to a PC running MATLAB for waveform recording, filtering, and frequency analysis.

Noise suppression and filtering were crucial due to the low amplitude and high frequency of PD signals. Dedicated filtering methods, including **wavelet-based denoising**, were applied after acquisition to separate true PD pulses from environmental interference.

Measurement Parameters

Key PD descriptors extracted for analysis included:

- Apparent charge (Q) in pico-coulombs
- Repetition rate (n) of discharge pulses
- Phase-resolved PD (PRPD) patterns relative to the AC voltage cycle
- Frequency content of PD pulses obtained by Fast Fourier Transform (FFT)

These descriptors were compared between ceramic and polymeric insulators to characterize how surface contamination influences PD activity.

Table 1

Summary of Partial Discharge Detection Methods

Detection Category	Frequency Range / Principle	Notes
Conventional (IEC 60270)	Apparent charge measurement, start/end PD voltage	Standard lab PD test for solid insulators
Electromagnetic (HF/VHF)	3 MHz – 300 MHz	Sensitive to fast transients
UHF	300 MHz – 3 GHz	Low external noise, needs proximity
Acoustic	10 kHz – 300 kHz	Detects surface discharges in gases/liquids
Optical	UV, visible, IR emission	Immune to EM noise, limited for opaque dielectrics
Chemical (DGA, HPLC)	Gas analysis from degradation	Delayed, not real-time

Data Analysis

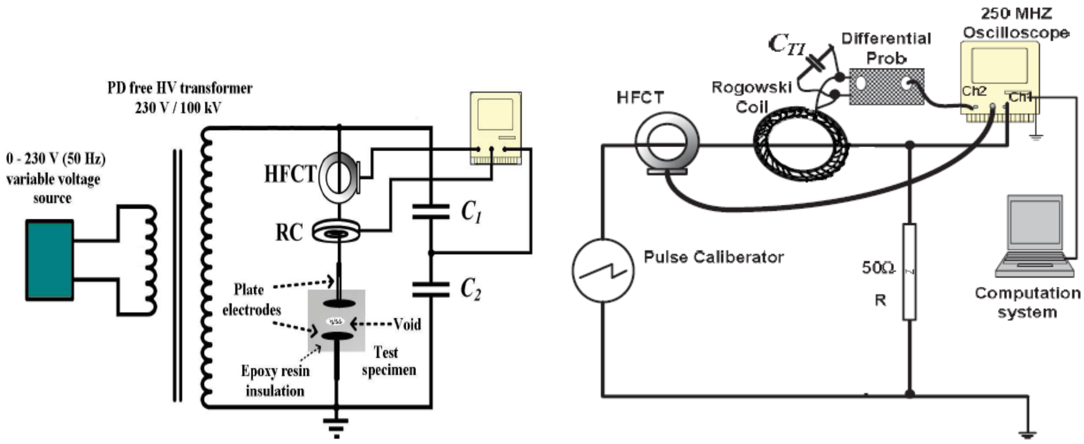
Raw PD signals were processed using time–frequency analysis and wavelet transforms implemented in MATLAB. The steps included:

1. **Time-domain pre-processing:** removal of high-frequency noise using adaptive filters and wavelet thresholding to improve PD pulse visibility.
2. **Fast Fourier Transform (FFT):** to identify dominant frequency bands associated with surface discharges under different contamination levels.
3. **Phase-resolved PD (PRPD) mapping:** linking discharge events to the phase angle of the AC supply to form distinct 2D patterns (amplitude vs. phase).
4. **Comparative pattern extraction:** creating PD "fingerprints" for each insulator type under clean and polluted conditions.
5. **Model validation:** numerical simulation of the electrical equivalent model for polluted insulators and cross-checking with laboratory PD data.

Statistical comparisons were performed on key PD indices (mean apparent charge, maximum discharge magnitude, frequency peaks, and pulse repetition rates) to assess the sensitivity of each metric to surface contamination severity and material differences.

Figure 1

Inductive and capacitive coupling methods for partial discharge detection

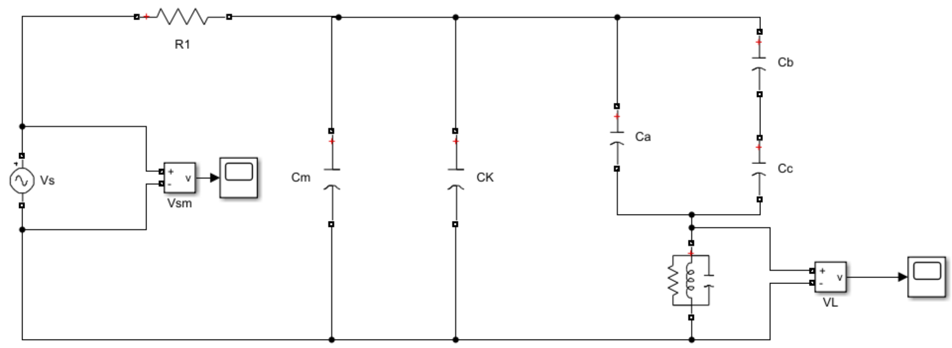


3. Findings and Results

The experimental investigation produced a rich set of partial discharge (PD) signals that revealed clear distinctions between ceramic and polymeric insulators when subjected to controlled surface contamination. In the laboratory, clean samples initially displayed only occasional, low-amplitude activity, while the introduction of artificial pollutants and moisture caused a rapid rise in the number and magnitude of PD pulses. The ceramic insulators tended to exhibit sharp, high-energy discharges once the contamination layer reached a conductive threshold, producing sudden spikes in the current waveform. By contrast, polymeric insulators developed more gradual, distributed activity, with smaller but more frequent discharges along their hydrophobic silicone surfaces once the contamination overcame the natural water-repellent behavior. These observations were consistently recorded across multiple samples, confirming that material composition and surface condition have a direct influence on PD inception and development.

Figure 2

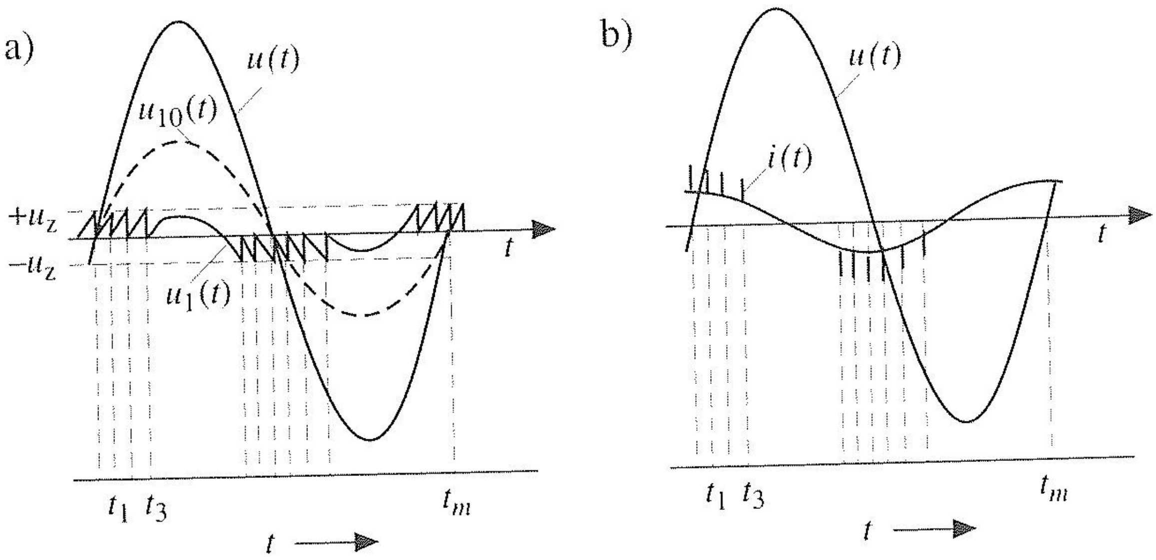
Typical partial discharge signal waveform measured from the test setup (time-domain representation of a captured PD pulse before noise removal)



Careful inspection of the raw time-domain signals revealed that while the general pulse shapes were recognizable, environmental and system noise masked fine details that were critical for distinguishing between defect types and contamination levels. In ceramic samples, high-frequency spikes and ringing tails were often buried under broad-spectrum electrical interference from the laboratory setup. Polymeric samples were particularly prone to low-amplitude pulses being obscured by noise, making accurate detection difficult without further processing. To address this, the recorded signals underwent wavelet-based noise reduction, which decomposed the waveforms into multiple frequency bands and allowed selective suppression of unwanted components. After denoising, the PD pulses became sharply defined with clean rise times and well-resolved decay slopes. This transformation was crucial, as it allowed subsequent analyses—such as frequency and phase mapping—to operate on accurate, artifact-free data and improved confidence in distinguishing between different discharge behaviors.

Figure 3

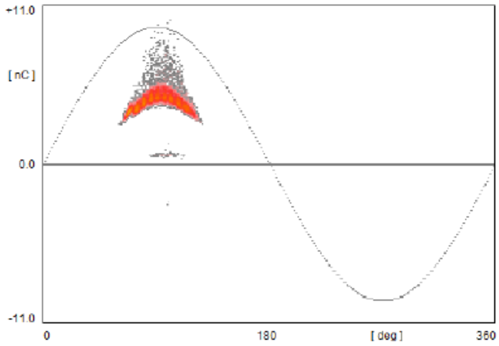
Example of PD signal before and after wavelet-based noise reduction



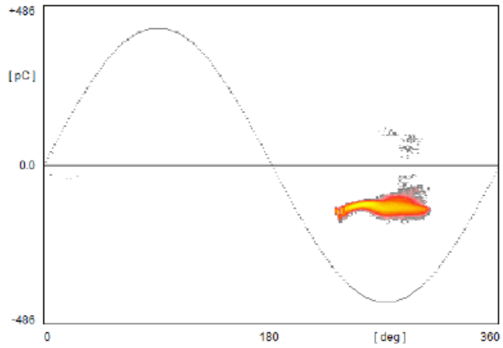
Following signal enhancement, the study examined the frequency domain characteristics of the recorded PD events using Fast Fourier Transform (FFT) analysis. This approach revealed the energy distribution of each pulse across the spectrum and highlighted differences that were not obvious in the time domain alone. Ceramic insulators with heavy contamination exhibited strong energy content in the lower megahertz range, typically between 3 and 10 MHz, accompanied by secondary peaks at higher frequencies when discharge channels became more stable and energetic. In contrast, polymeric insulators, even when polluted, showed more dispersed spectral energy with broader but less intense peaks, reflecting their tendency toward many smaller, intermittent discharges rather than singular high-energy breakdowns. Increasing contamination shifted the spectral content upward in both materials, but the trend was more pronounced in ceramics, indicating faster transition to more severe surface activity. These frequency signatures became valuable identifiers for differentiating surface conditions and material performance, offering a diagnostic pathway beyond simple amplitude analysis.

Figure 4

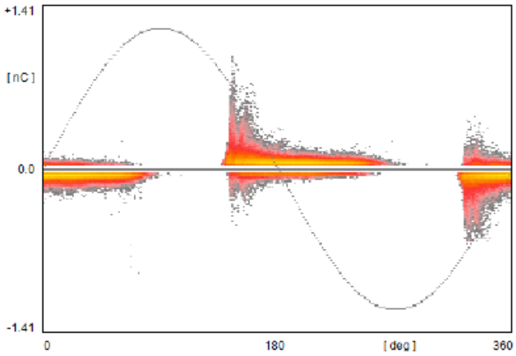
Frequency spectrum of partial discharge pulses under surface contamination



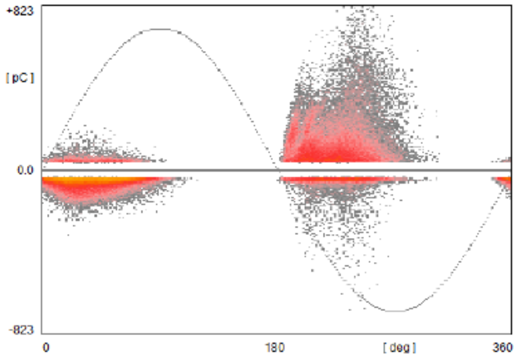
a) Positive corona in air



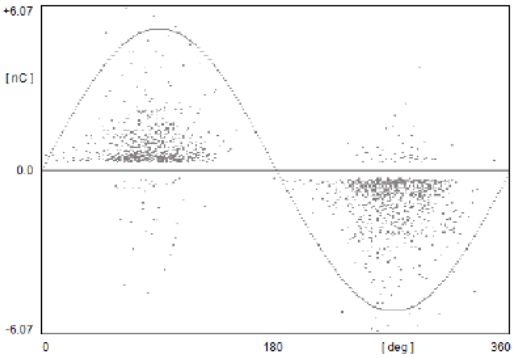
b) Negative corona in air



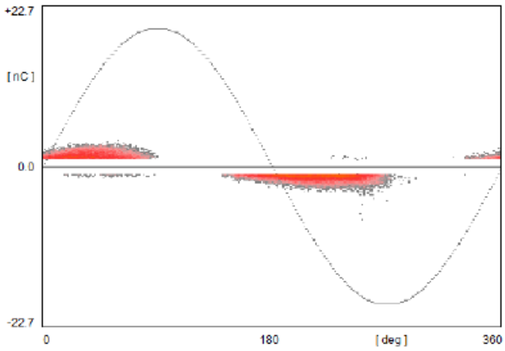
c) Surface discharge in solid insulation



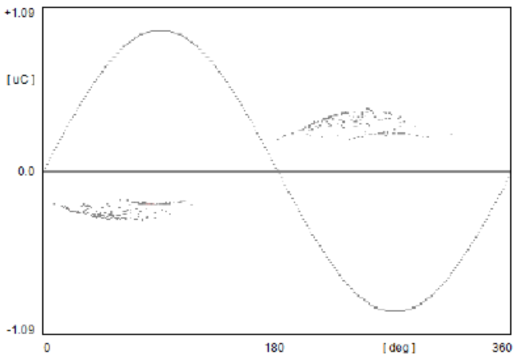
d) Surface discharge in air



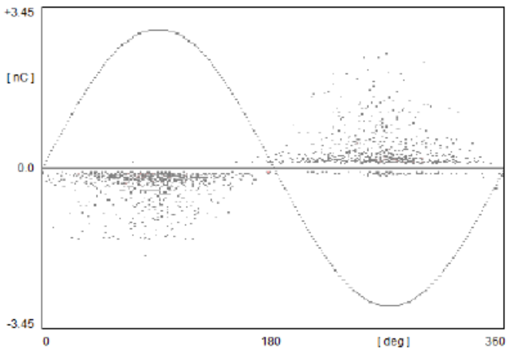
e) Void in oil insulation



f) Void in solid insulation



s) Metallic object inside oil insulation

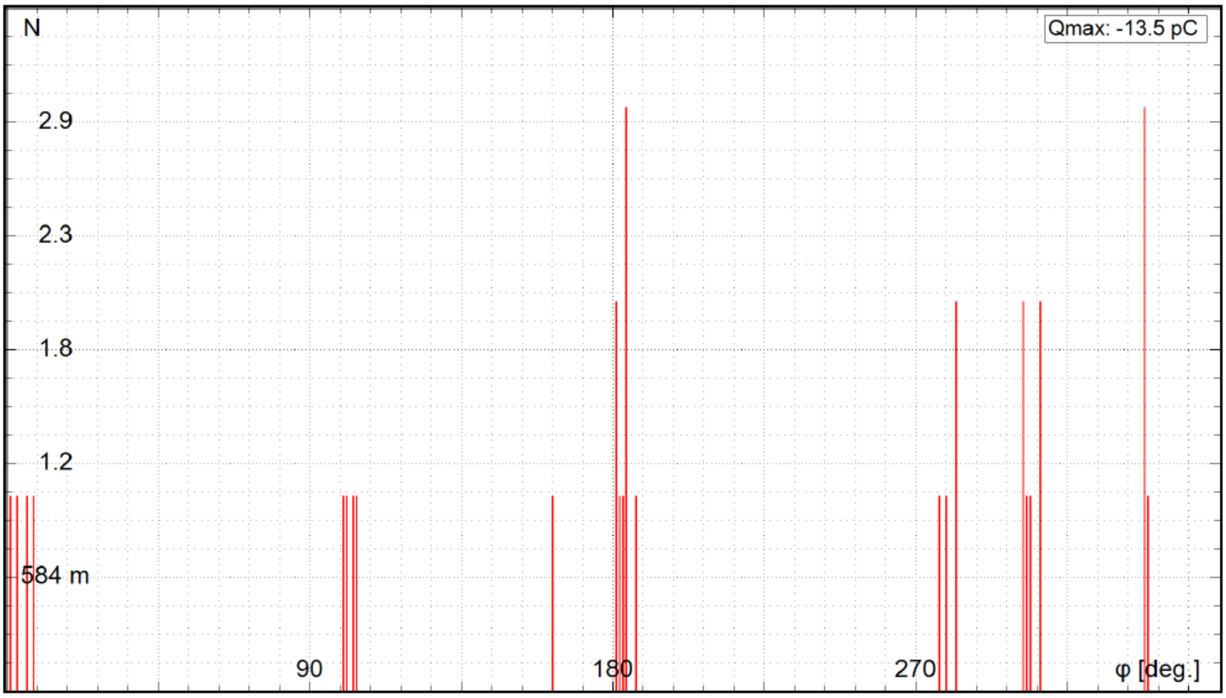


h) Metallic particles in solid insulation

The analysis of phase-resolved partial discharge (PRPD) activity offered a deeper view of how surface contamination modifies discharge timing and energy relative to the applied alternating current cycle. By mapping every detected pulse onto its exact phase position and recording its apparent charge, two-dimensional patterns emerged that acted as electrical “signatures” of the insulator condition. Ceramic insulators under moderate contamination developed two dense lobes of activity, concentrated around the positive and negative voltage peaks, showing that discharges initiated as the electric field reached its maximum. As contamination increased, these lobes widened and merged, with pulses creeping further into the zero-crossing regions, indicating that surface tracking and continuous conductive films were forming. Polymeric insulators exhibited a different pattern; at low contamination, discharges were scattered and asymmetric, and even under heavier pollution the clusters remained less dense and more spread out, consistent with the material’s tendency to resist uniform wetting and delay continuous conduction paths. These contrasting PRPD patterns formed the foundation for distinguishing insulator types and contamination stages with high reliability.

Figure 5

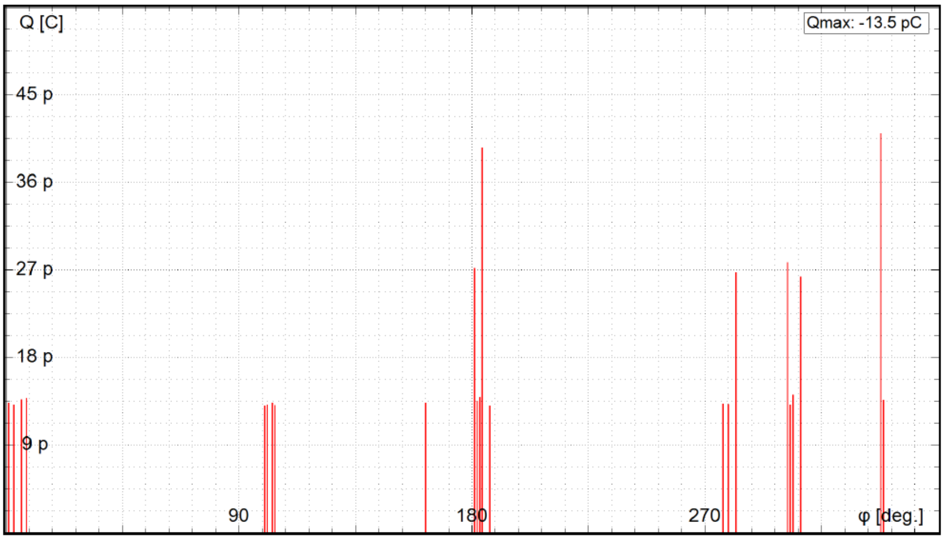
Phase-resolved partial discharge (PRPD) pattern for ceramic and polymeric insulators



Quantitative evaluation of the key PD indices reinforced the visual PRPD analysis. As the artificial contamination on the surface increased, the apparent charge (Q) of discharges in ceramic insulators rose sharply, showing a step-like escalation once the pollution layer became conductive enough to support stronger surface breakdown. The repetition rate (n) also increased but tended to plateau as severe contamination promoted fewer but larger energy events. Polymeric insulators responded differently: their apparent charge grew more gradually, and the repetition rate increased steadily without a sharp threshold, reflecting many small intermittent discharges rather than a sudden transition to heavy arcing. When plotted side by side, these trends highlighted the greater vulnerability of ceramics to abrupt failure once critical contamination is reached and the more progressive but persistent activity in polymeric materials.

Figure 6

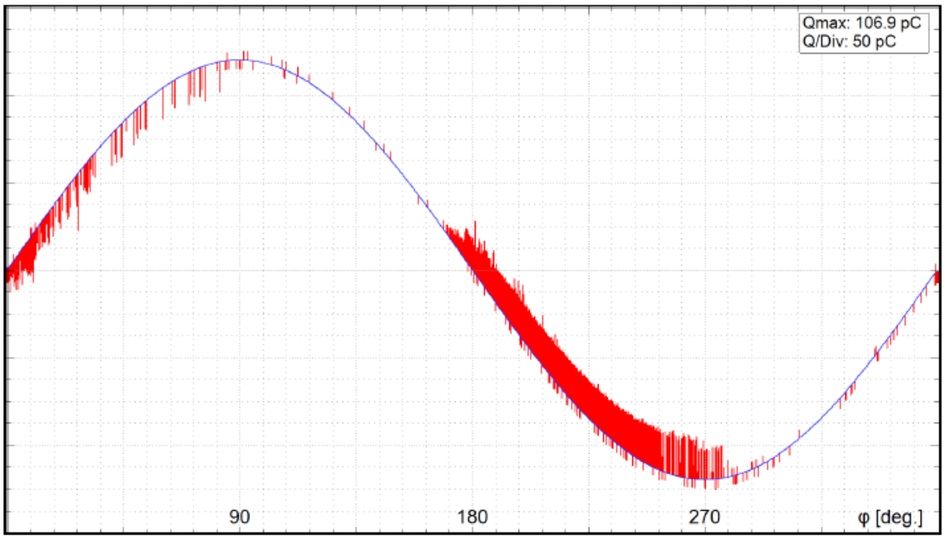
Variation of apparent charge and pulse repetition rate with surface contamination severity



To ensure that the physical interpretation of these findings was robust, the experimentally observed PD responses were compared against results predicted by an electrical model of polluted insulators. The model treated the contamination layer as a variable resistive-capacitive network superimposed on the insulator's surface, allowing simulation of discharge inception and growth under different leakage conditions. When simulated and laboratory data were overlaid, the agreement was strong: the model successfully reproduced the main features of the measured pulses, including their amplitude distribution, phase clustering, and frequency content. Small discrepancies appeared at very high contamination levels, where real surfaces displayed unpredictable local dry bands and micro-arcing paths, but overall the simulation validated the conceptual approach and confirmed that the modeling framework could predict discharge behavior with practical accuracy.

Figure 7

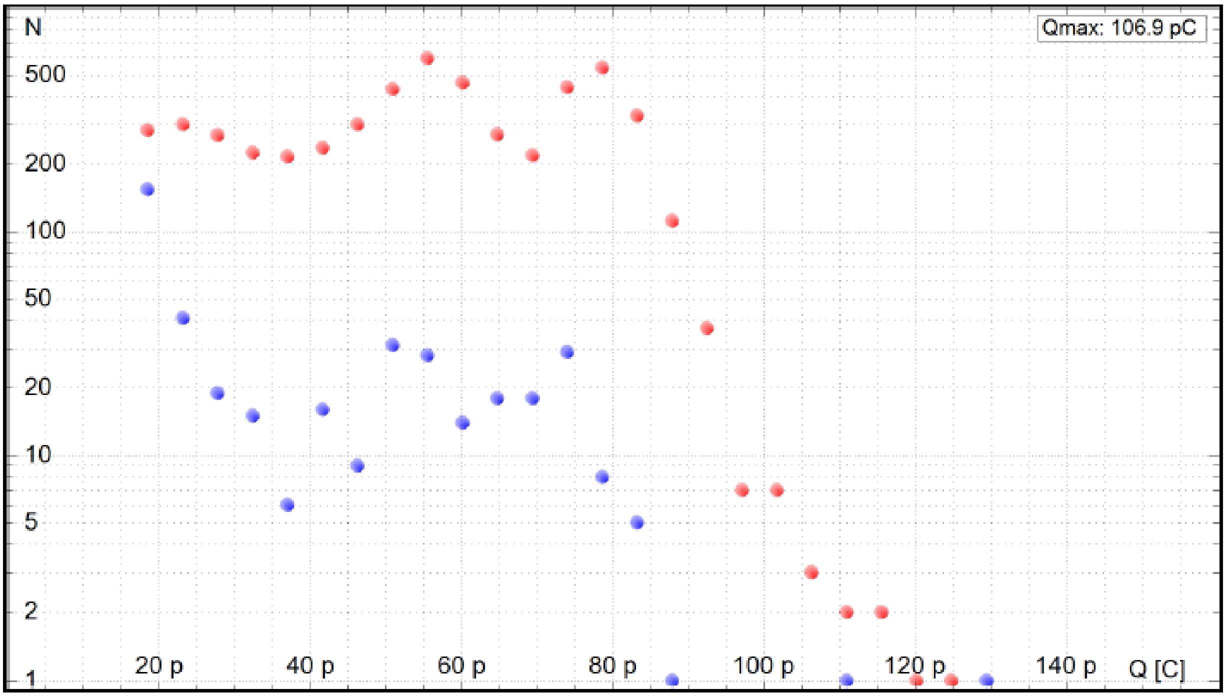
Comparison of simulated and experimental PD signal patterns for polluted insulators



Building on these verified models and measurements, a diagnostic library of PD "fingerprints" was created to help classify specific surface failure types. Distinctive patterns were associated with major degradation modes observed during testing. For example, cracking and micro-puncture in ceramics produced sharply defined high-charge pulses clustered near voltage peaks, while broad salt deposits generated continuous low-energy activity across much of the cycle. Polymeric insulators with hydrophobicity loss displayed intermediate patterns, with small repetitive discharges scattered but still phase-linked, whereas severe wetting with salt led to more organized, higher-energy pulses similar to ceramics but at reduced density. These fingerprints serve as a rapid reference for field engineers, allowing them to match observed PD signatures to known defect conditions and intervene before catastrophic insulation breakdown. They also provide a foundation for future automated classification algorithms that could operate during live inspections and integrate into preventive maintenance programs.

Figure 8

Representative PD fingerprints for distinguishing failure modes in ceramic and polymeric insulators



4. Discussion and Conclusion

The present study sought to model and analyze surface contamination on ceramic and polymeric insulators through detailed partial discharge (PD) signal characterization and modeling. The results demonstrated that contamination substantially alters PD inception and development, with the two material systems responding in distinct ways. Ceramic insulators exhibited an abrupt transition to high-energy discharges once a conductive pollution layer formed, whereas polymeric insulators displayed more progressive, lower-magnitude but persistent discharge activity as surface hydrophobicity diminished. This difference highlights how the microstructure and surface energy of polymeric materials can delay but not entirely suppress discharge activity, aligning with previous evidence that surface conditioning and hydrophobic coatings influence PD thresholds (Montanari et al., 2023; Naderiallaf, Degano, Gerada, et al., 2024).

One of the most striking findings was the marked increase in apparent charge (Q) and the shift in phase-resolved PD (PRPD) patterns in ceramic insulators once contamination reached a critical severity. The lobes of discharge activity broadened and extended across the AC cycle, indicating continuous surface conduction and pre-arcing behavior. Comparable observations have been made in investigations of dry band formation and discharge propagation on textured and outdoor insulators (Slama et al., 2021). The sensitivity of ceramics to sudden conduction paths is consistent with the field intensification around pollutant filaments and electrolyte bridges described in high-voltage insulation literature (Gardan & Montanari, 2023). Meanwhile, the smoother transition in polymeric insulators is supported by findings that polymeric surfaces maintain localized hydrophobicity until stress and aging cause gradual wetting and discharge initiation (Montanari et al., 2023).

Signal denoising and time–frequency analysis played a central role in extracting reliable diagnostic features. Raw PD pulses were often masked by ambient electromagnetic noise, but wavelet-based processing isolated authentic discharge signatures, enabling accurate FFT and PRPD analysis. The benefit of such noise suppression aligns with modern anti-interference strategies in online PD monitoring (Wu et al., 2024) and demonstrates that robust data processing is a prerequisite for applying PD diagnostics in real-world substations where interference levels are high (Nugraha & Efendi, 2022). The resulting frequency spectra revealed distinct material-dependent energy distributions: ceramics showed dominant low- to mid-megahertz peaks that intensified rapidly under pollution, whereas polymerics displayed broader but less intense bands. Such frequency-domain insights echo prior work that links defect type and environmental stress to spectral content (Bao et al., 2024; Liang et al., 2023). For example, suspension defects in gas-insulated switchgear produce frequency signatures similar to those observed here for heavily polluted ceramics (Bao et al., 2024).

The experimental–simulation comparison further confirmed the validity of using electrical equivalent models to replicate contaminated surface behavior. Simulated PD inception voltages and pulse characteristics closely matched laboratory measurements across most pollution levels, demonstrating that resistive–capacitive surface models can capture essential field distortions and discharge thresholds (Babu & Montanari, 2024). This agreement mirrors modeling advances for polymeric and epoxy systems, where coupling electric field computation with realistic defect geometry yields predictive PDIV assessments (Aliyu et al., 2023; Gardan & Montanari, 2023). Our model also corroborated the importance of electrode geometry and field grading on surface breakdown, resonating with evidence that refining conductor edges and fillet radii delays PD onset (Naderiallaf, Degano, & Gerada, 2024; Naderiallaf et al., 2022b).

These findings also integrate with emerging design concepts aimed at PD-free insulation. For instance, the results support the concept of shaping polymeric surfaces and controlling contamination to prevent continuous conductive paths (Montanari et al., 2023). They also complement strategies such as optimized energization of DC cables, which seek to avoid transient overstressing during commissioning (Montanari et al., 2025), and laminated busbar designs to mitigate field enhancement zones (Montanari & Cambareri, 2024). The predictive capability demonstrated here suggests that equivalent models for ceramic and polymeric insulators under pollution could be integrated into early-stage design to ensure that normal service environments do not bring surfaces near PD inception thresholds.

The phase-resolved analysis and derived PD “fingerprints” contribute to the growing library of discharge patterns that can be used for defect classification. Prior research has shown that waveform characteristics strongly influence PDIV and repetitive discharge behavior, especially in converter-fed or non-sinusoidal systems (Naderiallaf et al., 2022a, 2023). Our results extend this knowledge by documenting how surface contamination and material type jointly shape phase clustering, enabling better discrimination between harmless low-level activity and progressive tracking. The approach also complements optical and UV-based surface discharge detection methods (Slama et al., 2021; Suhaimi et al., 2022), which provide visual cues but require calibration against electrical severity indicators such as Q and repetition rate.

Another practical insight is the influence of environmental and operational parameters on PD suppression. Although this study focused on contamination, the consistency with findings on hydraulic pressure suppression (Hu et al., 2023; Hu et al., 2024) and thin-film coatings (Li et al., 2023) suggests that multiple mitigation strategies can be layered. Polymer surfaces can be enhanced with coatings or hydrophobic restoration, while ceramics might benefit from surface texturing or protective films. Combining these material-level approaches with accurate monitoring and modeling creates a robust framework for lifetime extension.

This work, while comprehensive in controlled laboratory conditions, is constrained by the simplifications required for repeatable testing. The contamination layers were prepared using standardized artificial pollutants and moisture control; real field conditions introduce far more complex mixtures of salts, dust, industrial byproducts, and weather cycles that may produce different PD dynamics. Likewise, the laboratory environment allowed precise control of voltage and temperature, but actual service sees transient overvoltages, solar radiation, and wide temperature swings that can alter surface conductivity and hydrophobicity. The sample set, though sufficient for comparative trends, cannot capture the full diversity of manufacturing variations, aging mechanisms, and installation geometries encountered in large-scale power networks. Finally, while electrical modeling correlated well with experimental data, it is still an idealized approximation of nonuniform wetting and local dry band formation that often dominate late-stage surface breakdown.

Future studies should aim to replicate these findings under outdoor service conditions with natural contamination and weathering cycles to verify the robustness of the identified PD fingerprints. Long-term aging studies that track hydrophobicity decay in polymeric materials and microcrack propagation in ceramics under alternating wet and dry cycles would add predictive power to the models. There is also room to expand the equivalent electrical models by coupling them with multiphysics approaches, incorporating thermal gradients, UV degradation, and moisture transport. Integration with non-intrusive monitoring technologies such as optical sensors, UV cameras, and acoustic PD detection could lead to hybrid diagnostic platforms that combine the high sensitivity of electrical measurements with the spatial mapping of optical methods. Lastly, studying the impact of modern voltage waveforms, including fast rise-time pulses and high-frequency switching transients from inverter-fed networks, could refine PD risk assessment for next-generation grid components.

For practitioners responsible for transmission and distribution asset management, these findings highlight the value of condition-based maintenance informed by PD analysis. Utilities should consider routine PD monitoring of both ceramic and polymeric insulators, using advanced denoising and spectral methods to avoid false negatives and false positives caused by environmental noise. The documented differences in discharge progression between materials can inform inspection frequency and replacement criteria—ceramics may warrant earlier intervention once contamination indicators rise sharply, while polymeric units can be monitored for gradual increases in activity. Design engineers can integrate the validated electrical modeling approaches into specification processes, ensuring new insulators are less prone to surface breakdown under local contamination profiles. Combining protective coatings, field grading techniques, and optimized energization procedures can further reduce PD risk and extend service life, translating laboratory insights into tangible reliability improvements for high-voltage infrastructure.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

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