Al-Farouk journal of sciences
Volume (2), Issue (4) (Spt, 2026)
ISSN: 3135-2359

مجلة الفاروق للعلوم
المجلد (2) العدد 4 سبتمبر 2026
ردمد: 3135-2359

From Microscopic Degradation to Grid Resilience: A Comprehensive Analysis of Surface Tracking Mechanisms and Predictive Mitigation in Polymeric Insulators

Abdelati M. Taher Jermi
Department of Renewable Energy, Faculty of Natural Resource Engineering, University of Zawia, Libya
a.jermi@zu.edu.ly
https://orcid.org/0009-0007-3489-569X

تاريخ الاستلام: 2026/8/01 تاريخ المراجعة 2026/8/12 تاريخ القبول:2026/8/28- تاريخ النشر: 2026/9/11

Abstract

This study investigates surface tracking phenomena in polymeric insulators, focusing on how material composition, design integrity, and operational conditions influence their performance and reliability in high-voltage applications. Polymeric insulators are increasingly favored in modern power systems due to their lightweight nature, hydrophobic properties, and resistance to vandalism. However, their susceptibility to surface degradation surface tracking poses significant operational challenges. The research emphasizes the critical role of each insulator component, including the weather-resistant polymeric housing, reinforced glass fiber (RBGF) core, metal end fittings, and sealing interfaces. Any deterioration, especially at the junctions between polymeric and metallic parts, can initiate surface tracking, potentially leading to dielectric failure, current leakage, and outages. Through analysis of structural composition and field performance, the study underscores the importance of material selection, proper engineering design, and proactive maintenance strategies. Enhancing understanding of surface tracking mechanisms is vital to mitigating operational risks and ensuring long-term stability and safety in electrical power networks.

Keywords: *Polymeric insulators, surface tracking, dielectric failure, RBGF, electrical maintenance*

1. Introduction

As global power grids continue to expand and evolve, the demand for advanced insulation solutions capable of enduring extreme environmental and electrical stresses has become increasingly critical [1], [2]. Among the key components ensuring the safe and efficient operation of high-voltage systems are electrical insulators. In recent years, polymeric insulators have gained widespread adoption as a modern alternative to traditional ceramic and glass counterparts, thanks to their superior mechanical flexibility, lighter weight, hydrophobic surfaces, and resistance to pollution and vandalism [1,2]. Despite these advantages, polymeric insulators are not without limitations. Their performance can deteriorate over time due to environmental exposure, contamination, and electrical stress. One of the most critical forms of degradation is **surface tracking** a phenomenon where dry-band arcing across the insulator surface leads to carbonized paths that compromise dielectric strength, resulting in current leakage or complete failure [3]. This degradation not only threatens the reliability of the power system but also presents substantial operational and safety risks, especially in coastal, desert, and highly polluted environments [4,5].

This study aims to provide a comprehensive analysis of the surface tracking phenomenon in polymeric insulators. It begins by examining the material composition and structural design of these insulators, highlighting the roles of housing materials (e.g., silicone rubber and EPDM), RBGF cores, metal end fittings, and sealing interfaces [5]. The paper then explores the causes and progression of surface tracking, evaluates its impact on operational performance, and discusses effective strategies for risk mitigation through proper material selection, design optimization, and preventive maintenance practices [6]. Through this investigation, the study seeks to contribute to a deeper understanding of the factors influencing insulator reliability and to support efforts toward safer, more resilient power infrastructure.

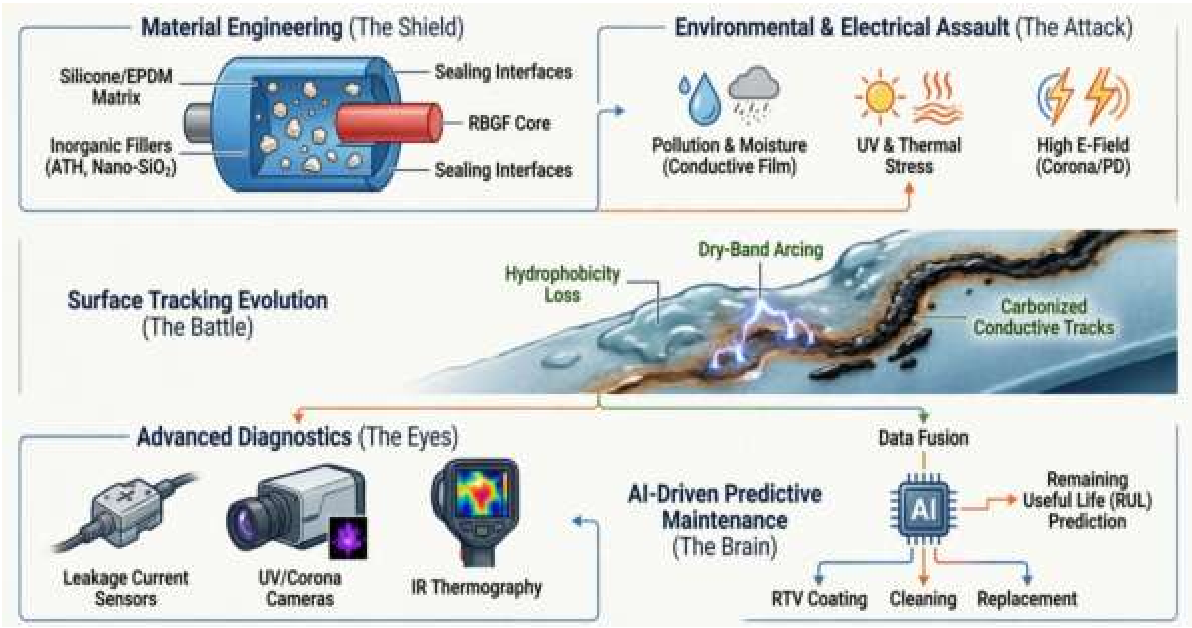

Figure 1 the workflow method of the research

Figure 1 above illustrates the lifecycle of surface tracking in polymeric insulators, beginning with the material engineering "shield" (silicone/EPDM matrix, ATH fillers, and RBGF core) designed to resist environmental and electrical "attacks" like pollution, UV stress, and corona discharge. When these stressors overwhelm the material, they trigger the "battle" phase of surface tracking evolution, characterized by hydrophobicity loss, dry-band arcing, and the formation of permanent carbonized conductive tracks. To combat this degradation, utilities deploy advanced diagnostic "eyes," including leakage current sensors, UV cameras, and IR thermography, to detect early signs of insulation failure. The collected data is then fused and analyzed by AI-driven predictive maintenance systems, the "brain," to accurately calculate the insulator's Remaining Useful Life (RUL). This enables proactive, data-informed interventions such as RTV coating, cleaning, or replacement, ensuring long-term grid resilience and preventing catastrophic dielectric breakdown.

2. Material Composition of Polymeric Insulators

The structural integrity and operational reliability of polymeric insulators are fundamentally governed by the design and compatibility of their constituent materials. These components must work in concert to provide both robust mechanical support and effective electrical insulation under a wide range of environmental and electrical stresses [2]. “A typical polymeric insulator, as shown in Figure. 2 below, consists of the following primary components:”

:

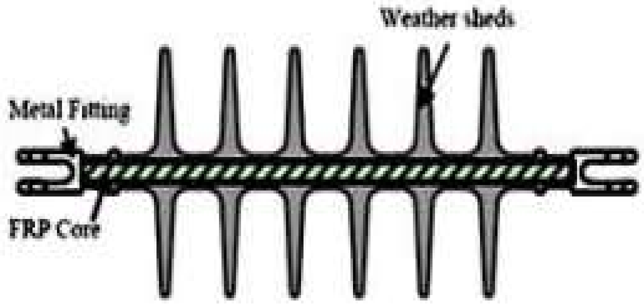

Figure 2. Structure of a Polymer Insulator [20]

- Housing Material: The external sheath is commonly fabricated from hydrophobic and weather-resistant polymers such as silicone rubber or ethylene propylene diene monomer (EPDM). These materials offer excellent resistance to ultraviolet radiation, thermal cycling, and environmental pollution, making them ideal for outdoor high-voltage applications [1].
- RBGF Core: At the core of the insulator lies a reinforced glass fiber rod (RBGF), which is responsible for bearing mechanical loads such as tension and bending forces. This core provides the essential structural strength needed to maintain performance under both static and dynamic stresses [3].
- Metal End Fittings: Made typically from galvanized steel or aluminum alloys, the end fittings serve as the mechanical and electrical interface between the insulator and the supporting electrical structure. Their design must ensure a secure, corrosion-resistant connection capable of withstanding mechanical stresses without compromising insulation [5].
- Sealing Interfaces: The junctions between the polymeric housing and the metallic end fittings are sealed using specialized bonding agents or rubber-based materials. These seals are critical for preventing moisture ingress, which can lead to partial discharges, surface tracking, or even catastrophic failure if left unmanaged [6].

The selection, compatibility, and long-term stability of these materials are essential to ensuring the durability and surface tracking resistance of polymeric insulators. Any degradation or mismatch in material properties at the housing-to-fittings interface can become a vulnerable point that accelerates surface deterioration and poses serious operational risks. Therefore, material engineering plays a pivotal role in enhancing the performance and service life of polymeric insulators in modern power systems.

3. Surface Tracking and Degradation Mechanisms

Surface tracking is a critical failure mode in polymeric insulators, characterized by the development of **carbonized, conductive paths** along the insulator surface. These paths are typically initiated by partial discharges and sustained by the presence of environmental contaminants and surface moisture. As these conductive channels propagate, they compromise the dielectric properties of the insulation, eventually leading to electrical breakdown, current leakage, and service interruptions [3,6]. Several interrelated degradation mechanisms contribute to the onset and progression of surface tracking:

- Electrical Stress: High-voltage electric fields induce partial discharges in localized weak zones, which gradually erode the polymer surface and initiate micro-cracking. These discharges are particularly intense under dry-band arcing conditions, often observed in polluted or humid environments [7].
- Environmental Contamination: Dust, salt deposits, and moisture in coastal or industrial zones form semi-conductive films on the surface of the insulator. These films facilitate leakage currents, which generate localized heating and promote surface carbonization and tracking [8].
- Ultraviolet (UV) Radiation: Prolonged exposure to solar radiation causes photo-oxidative degradation of polymer chains, resulting in surface embrittlement, loss of hydrophobicity, and increased susceptibility to discharge activity [9,10].
- Thermal Aging: Elevated operational temperatures and frequent thermal cycling accelerate the chemical aging of the polymeric matrix. This process leads to material hardening, cracking, and a breakdown of the polymer's insulating properties over time [11].

A thorough understanding of these degradation pathways is essential for developing effective monitoring, diagnostic, and maintenance strategies. Early detection of surface tracking indicators can enable timely interventions that mitigate risk and extend the service life of polymeric insulators in harsh field conditions.

4. Operational Risk Assessment and Maintenance Strategies

The increasing deployment of polymeric insulators in high-voltage power systems demands a proactive approach to risk assessment and maintenance, particularly in environments where contamination, humidity, and electrical stress converge. The degradation mechanisms such as surface tracking, erosion, and moisture ingress can result in cumulative damage that jeopardizes both system reliability and personnel safety as illustrated in the Figure 2 [1,3].

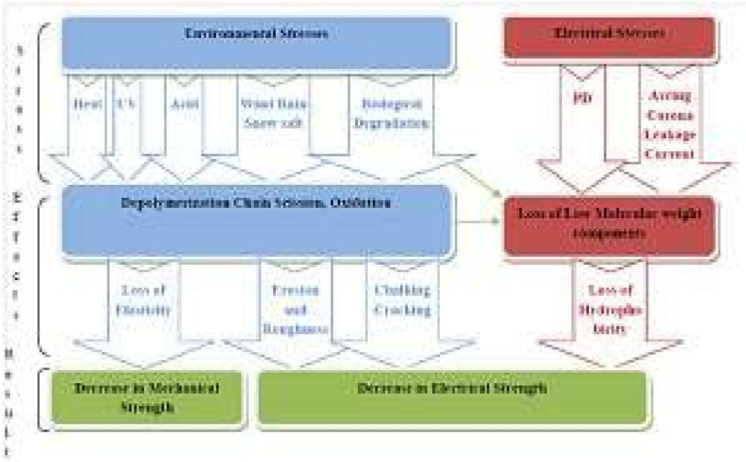

Figure 3. Effects of degradation on polymeric insulators [11].

4.1 Operational Risk Factors

Polymeric insulators are particularly vulnerable under the following operational conditions as illustrated in the Figure 4 below.

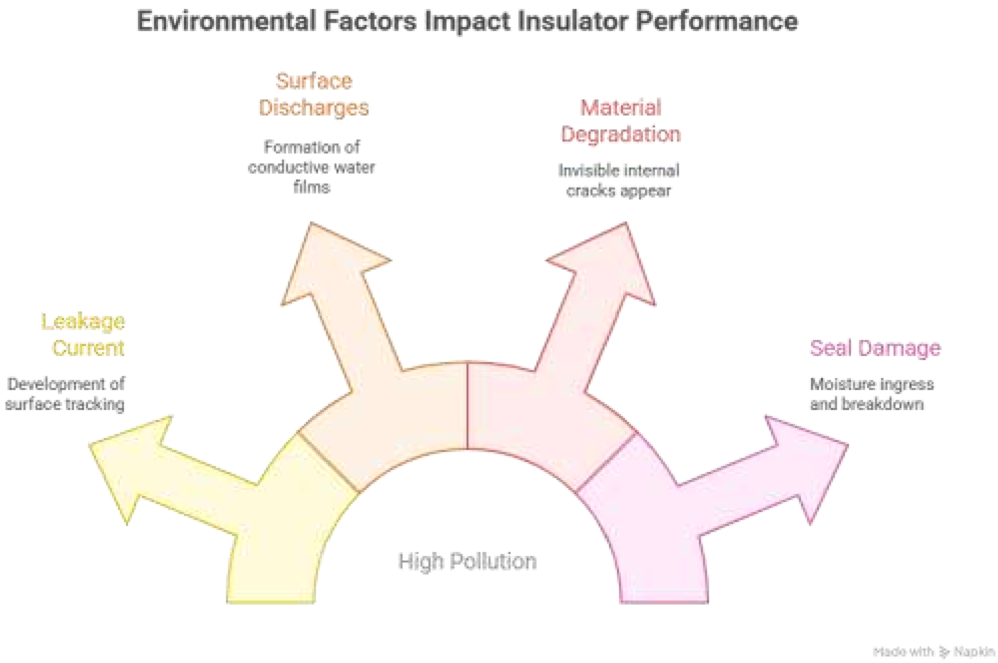

Figure 4. Shows Environmental Factors Impact Insulator Performance

- High Pollution Zones: Urban, coastal, or industrial areas with airborne salts and particulates pose a higher risk of leakage current development and surface tracking.
- Humidity and Rain Exposure: Frequent wetting–drying cycles accelerate the formation of conductive water films and dry bands, contributing to surface discharges and carbonization [12, 13].

- Aging Infrastructure: Long service durations without monitoring increase the probability of invisible material degradation, such as internal cracks or hydrophobicity loss.
- Mechanical Stress: Improper handling during installation or mechanical fatigue over time can lead to seal damage, facilitating moisture ingress and interface breakdown.

These factors collectively raise the risk of flashovers, insulation failure, unplanned outages, and costly equipment damage. Therefore, a structured and evidence-based risk evaluation is essential to maintain operational continuity and safety.

4.2 Preventive Maintenance and Monitoring Strategies

To mitigate these risks, utilities must implement preventive and predictive maintenance programs based on real-time diagnostics and material performance indicators as illustrated in the Figure 5 below:

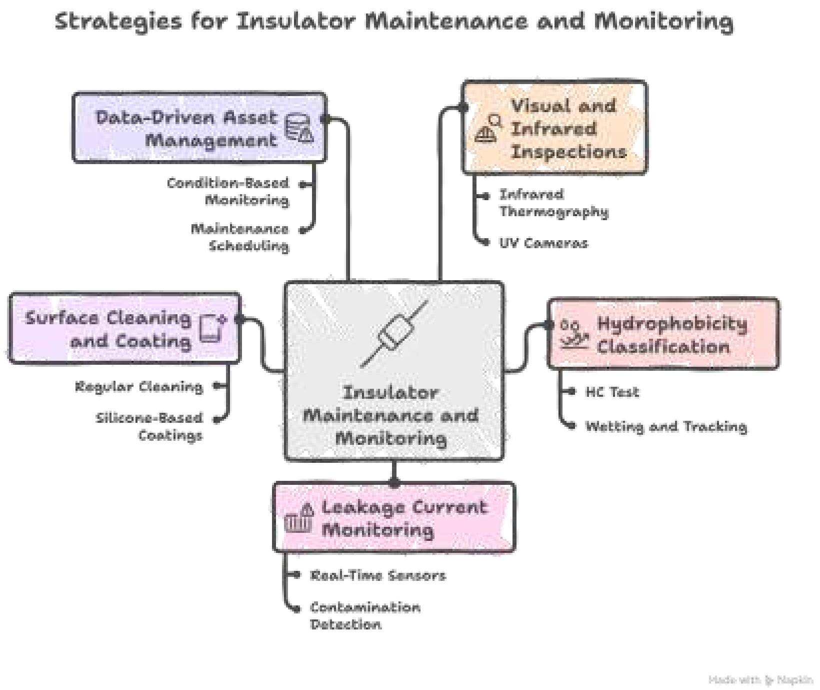

Figure. 5. Shows Strategies for Insulator Maintenance and Monitoring

- Visual and Infrared Inspections: Routine site inspections using infrared thermography and UV cameras can detect surface heating, corona discharges, and early signs of surface degradation [14, 15].
- Hydrophobicity Classification (HC Test): Periodic testing of surface hydrophobicity helps assess the aging level of the housing material and its susceptibility to wetting and tracking.
- Leakage Current Monitoring: Installing sensors to monitor leakage currents in real-time allows early detection of contamination-induced tracking and timely cleaning or replacement of insulators [16, 17].
- Surface Cleaning and Coating: In high-risk zones, regular cleaning of contaminants and the application of silicone-based coatings can restore surface properties and extend service life.

- Data-Driven Asset Management: Integrating condition-based monitoring data into asset management systems enables risk-informed decision-making regarding maintenance scheduling and insulator replacement.

4.3 Strategic Implications

The integration of these strategies into maintenance frameworks significantly reduces the likelihood of unplanned outages and improves the overall resilience of electrical networks. Moreover, it allows for a cost-effective lifecycle management approach, where resources are directed toward components that demonstrate actual risk of failure [18, 19, 20, 21].

5. The Andrinov Mechanism of Polymeric Insulator Degradation

One of the critical chemical pathways contributing to the long-term degradation of polymeric insulators, particularly those based on silicone rubber, is known as the Andrinov mechanism. This mechanism is especially relevant in the context of thermal-oxidative aging, where polymeric materials are subjected to moderately elevated temperatures in the presence of oxygen conditions commonly encountered during extended field service of outdoor insulators. The degradation process is initiated by the oxidative cleavage of silicon–carbon (Si–C) bonds, a reaction that begins to occur at relatively low temperatures (typically below 149°C). Under aerobic conditions, oxygen interacts with the silicone polymer chains, leading to the formation of reactive free radicals and peroxide compounds. These peroxides decompose into formaldehyde (HCHO) and hydroxide ions (OH^-), both of which act as reactive intermediates that drive a cascade of degradation reactions [12, 22, 23]. The generated hydroxide ions further react with methyl side groups present in the polydimethylsiloxane (PDMS) backbone common in silicone rubber formulations leading to progressive scission of polymer chains. This process ultimately results in the formation of amorphous silica (SiO_2) deposits on the surface of the insulator, which, although chemically inert, signify irreversible damage to the polymer structure.

The consequences of this degradation are multifold:

- Surface Embrittlement: Loss of elasticity and mechanical flexibility due to crosslink breakdown.
- Hydrophobicity Loss: Deterioration of the surface's ability to repel water, increasing susceptibility to wetting and tracking.
- Microscopic Surface Roughness: Formation of pits and irregularities that act as initiation points for surface discharges.

The rate of formaldehyde evolution and silica formation is significantly influenced by ambient thermal conditions. Studies have shown that higher operational temperatures accelerate the oxidation reactions, directly correlating with an increased likelihood of surface tracking and leakage current formation [3]. Furthermore, as the silicone surface deteriorates, it becomes more vulnerable to environmental contamination. Conductive deposits such as salt, industrial pollutants, and dust can accumulate in the roughened regions, forming a conductive bridge between the high-voltage electrodes. This bridge exacerbates leakage current flow, initiates localized dry-band arcing, and accelerates the propagation of surface tracking a phenomenon tightly linked with the Andrinov degradation pathway [12, 24, 25, 26]. The Andrinov mechanism highlights the chemical vulnerability of silicone-based polymeric insulators under thermal and oxidative stress. It underscores the importance of material stabilization, environmental sealing, and temperature management in minimizing long-term degradation and preserving the operational integrity of insulators deployed in demanding field conditions [27].

6. Thermal Degradation under Inert Atmospheric Conditions

Thermal degradation of polymeric insulators is a complex phenomenon that varies significantly depending on the surrounding atmospheric conditions. While oxidative environments (e.g., air) initiate degradation at relatively moderate temperatures due to the availability of oxygen, inert atmospheres such as nitrogen (N_2) or argon (Ar) require significantly higher thermal thresholds, often exceeding 400°C, to trigger decomposition processes [13]. In oxidative environments, the polymer backbone undergoes chain scission and oxidative cleavage, leading to the formation of silica (SiO_2) residues, carbon oxides (CO, CO_2), and water vapor. These reactions not only erode the insulating surface but also degrade hydrophobicity, which is essential for preventing surface tracking under wet or polluted conditions. Conversely, in inert conditions, the absence of oxygen inhibits oxidative chain reactions. Instead, the degradation mechanism involves thermal depolymerization of the silicone matrix, resulting in the release of volatile siloxane oligomers. While oxidation is largely suppressed, localized carbonization may still occur due to thermal stress, especially during prolonged exposure to high temperatures or under concentrated heating zones [3]. This can lead to the formation of carbonaceous tracks on the surface, which act as precursors to surface leakage currents when re-exposed to moisture or voltage stress.

6.1 Mitigation through Inorganic Fillers

To combat thermally induced degradation, especially in high-voltage outdoor applications, the integration of inorganic fillers into the polymer matrix has emerged as a highly effective strategy. Fillers such as alumina trihydrate (ATH) and precipitated silica (SiO_2) contribute significantly to enhancing the thermal and dielectric stability of polymeric composites [4]. Their benefits include:

- Elevated Thermal Resistance: Fillers act as thermal buffers, delaying the onset of decomposition and reducing heat-induced chain scission.
- Suppression of Flame Propagation: Under arc discharge or flashover conditions, fillers act as heat sinks and physical barriers, mitigating combustion and surface damage.
- Improved Erosion Resistance: The presence of stable inorganic particulates enhances resistance to arc-induced erosion and dry-band arcing phenomena.

These enhancements make filler-reinforced polymeric insulators particularly suitable for demanding service conditions, where they are continuously subjected to thermal cycling, pollution stress, and electrical loading. By limiting both thermal aging and surface carbonization, such material systems extend the operational lifespan of the insulator while maintaining functional reliability in the field.

7. Corona-Induced Tracking and Its Impact on Polymeric Insulators

Corona discharge is a localized ionization phenomenon that commonly arises in high-voltage systems, particularly when the electric field intensity around conductors exceeds the dielectric strength of air. This effect becomes pronounced when operating voltages surpass 3.5 kV, causing the surrounding air to become partially ionized. The process leads to the emission of ozone (O_3), ultraviolet (UV) radiation, nitrogen oxides, localized heating, and electromagnetic noise, even in the absence of a measurable leakage current [14]. The ionization of nitrogen molecules produces a visible bluish or purplish glow near the conductor commonly referred to as the *corona glow*. When humidity is present, secondary reactions may occur between nitrogen oxides and water vapor, forming nitric acid (HNO_3). This compound, in conjunction with ozone, initiates aggressive chemical attacks on the surface of rubber-based polymeric insulators, gradually deteriorating their structural and dielectric integrity [1, 28, 29, 30]. Unlike direct surface tracking caused by conductive contaminants, corona-induced tracking is often insidious and progressive, leaving behind no initial current path. However, the ionized air around the corona is highly conductive. When a transient bridge form either toward another conductor or toward ground potential a flashover can occur. The energy released during this discharge carbonizes the polymer surface, forming a permanent conductive track. This carbon track significantly reduces the insulation's resistance, creating conditions for repeated discharge events and long-term degradation [15]. One of the challenges in corona detection is that the process is often silent and invisible to the naked eye, with ozone being the only immediate by-product. However, over time, physical indicators begin to emerge, particularly on silicone rubber or EPDM-based insulators. A white fibrous or chalky residue—often rich in oxidized compounds—is deposited on the surface. Analytical studies have shown this residue to be electrically conductive, creating localized arcing zones and acting as a seed for surface erosion and dry-band arcing [11]. Coronas are frequently associated with improper cable spacing, sharp edges, damaged insulation, or conductor bundling conditions that distort the electric field and facilitate partial discharges. In outdoor environments, especially where contamination and high humidity coexist, these effects are magnified, accelerating the onset of dielectric failure as illustrated in the Figure 6 below.

Figure 6: Dust deposit on tie- wrapped cables [16]

Corona-induced degradation represents a subtle yet potent threat to the operational life of polymeric insulators. Its progression often unnoticed during early stages culminates in surface carbonization, insulation failure, and potential flashover events. Effective mitigation requires both improved geometric design of conductors to minimize field distortion and regular diagnostic inspections, such as UV imaging, corona cameras, and surface residue analysis.

8. Water Treeing and Electrical Treeing in Dielectric Materials

Among the most insidious and destructive degradation phenomena affecting polymeric insulation in high-voltage underground cables and moisture-prone environments are water treeing and electrical treeing. These mechanisms significantly undermine the dielectric strength and long-term reliability of insulation systems, often progressing unnoticed until catastrophic failure occurs.

8.1 Water Trees: Microscopic Pathways of Degradation

Water trees are microstructural degradation features that develop within dielectric materials cross-linked polyethylene (XLPE) when exposed to long-term moisture and sustained electrical stress. They originate at pre-existing defects, such as voids, contaminants, or mechanical imperfections, and appear as plume-like structures composed of a dense network of microscopic, partially conductive tubules [17]. These structures can only be observed through scanning electron microscopy (SEM) and are characterized by their branching, tree-like morphology. The tubules form as a result of electrochemical interactions between water molecules and the polymer chains, which are accelerated by the alternating electric field. Over time, the accumulation of these water-filled microcavities creates a semiconducting path that facilitates localized electric field enhancement, eventually leading to partial discharges and dielectric breakdown [18].

8.2 Electrical Trees: Macroscopic Precursor to Failure

In contrast, electrical trees are formed purely by electrical stress, even in the absence of moisture. They typically initiate at regions of surface roughness, voids, or impurities within the dielectric, where field enhancement causes progressive electrical breakdown of the material. These trees grow as branched, dark carbonized channels, often visible to the naked eye in advanced stages. The development of electrical trees is closely tied to rapid voltage transients, such as those occurring during switching operations or lightning impulses, which induce steep field gradients across the insulation. As the tree structure advances, it eventually bridges the electrodes, forming a conductive path that precipitates full insulation failure [4,31]. Electrical treeing can originate from water tree precursors. Once the tree-like microcavities of a water tree are subjected to sufficient electrical stress, they may transition into electrical trees, leading to rapid deterioration. The carbonized tracks left behind during this process are highly conductive and permanently compromise the insulation's dielectric properties [2]. The figure 7. (adapted from [Wikipedia – Electrical Treeing] (https://en.wikipedia.org/wiki/Electrical_treeing)) illustrates an advanced stage in the evolution of electrical treeing. At this stage, the tree channels have undergone extensive carbonization, as indicated by their darkened morphology. The formation of these carbonized, electrically conductive pathways results in a permanent breakdown of the dielectric, rendering the restoration of its insulating properties unattainable.

Figure 7: Treeing in underground cable insulators

8.3 Classification of Electrical Trees

Electrical trees are typically classified into two major forms:

- Bow-Tie Trees: These originate within the bulk of the dielectric and propagate outward toward both electrodes. Their growth is typically constrained due to limited oxygen availability, and they rarely result in complete insulation bridging. Bow-tie trees are often associated with partial discharges that are confined but still indicative of progressive degradation [19].
- Vented Trees: These initiate at the electrode-insulation interface and grow toward the opposite electrode, aided by the presence of air or moisture, which facilitates oxidation and carbonization of the propagating channels. Vented trees are considered the dominant cause of insulation failure in aged systems, as they are capable of spanning large dielectric distances and forming conductive bridges.

8.4 Detection and Implications

The presence and progression of both water and electrical trees can be detected through partial discharge (PD) measurements, which serve as a non-destructive diagnostic tool for assessing internal dielectric deterioration. The detection of PD activity near known defect zones is a reliable indicator of treeing phenomena and can inform preventive replacement strategies [32, 33, 34, 35]. Both mechanisms though distinct in origin converge in their outcome: the formation of conductive pathways that facilitate surface tracking, reduce insulation integrity, and compromise system reliability. Understanding their formation and implementing effective field grading, moisture barriers, and condition monitoring systems are essential for mitigating their impact in high-voltage polymeric applications [36, 37].

9. Conclusion and Recommendations

9.1 Conclusion

This study has comprehensively explored the phenomenon of surface tracking in polymeric insulators, with a focus on the material composition, environmental interactions, and operational stressors that contribute to performance degradation. Through a critical review of the mechanisms such as thermal degradation, corona-induced tracking, and treeing phenomena (both water and electrical) the analysis highlights the multidimensional nature of insulation failure in high-voltage systems. As power systems continue to evolve toward higher voltages, harsher environments, and more compact designs, the longevity and reliability of polymeric insulators will remain a cornerstone of grid integrity. A deeper understanding of surface tracking mechanisms combined with material innovation, intelligent diagnostics, and evidence-based engineering will be essential to minimize insulation-related failures and ensure the sustainability of modern electrical infrastructure.

Key findings reveal that

- Material formulation, particularly the type and concentration of inorganic fillers (e.g., SiO_2, ATH), plays a pivotal role in enhancing the thermal, electrical, and erosion resistance of polymeric insulators.
- Environmental stressors, including moisture, pollution, UV radiation, and partial discharge activity, accelerate surface erosion and tracking path formation, particularly in outdoor and high-altitude installations.
- Thermal degradation in inert vs. oxidative atmospheres results in different decomposition pathways and byproducts, affecting the rate and severity of surface damage.
- Corona discharges, even in the absence of leakage current, produce ozone and nitric acid, leading to rubber-based insulation deterioration through surface carbonization and ionized dust formation.
- The development of water trees and electrical trees both as microscopic and macroscopic degradation patterns are strongly associated with dielectric failure in polyethylene-based insulation used in underground and high-voltage cables.

The collective impact of these mechanisms ultimately undermines the insulating integrity, leads to irreversible carbonized tracking paths, and compromises the operational reliability of power transmission and distribution systems.

9.2 Recommendations

Based on the insights gained through this study, the following **practical and research-oriented recommendations** are proposed:

A. Material Design and Engineering

Enhance polymer formulations with high-performance inorganic fillers (e.g., nano-silica, ATH, boehmite) to increase thermal stability, suppress arc propagation, and reduce tracking susceptibility.

Develop **hybrid composite systems** that incorporate both hydrophobic and arc-resistant characteristics, especially for outdoor applications

Apply **surface coatings or chemical treatments** to reduce moisture absorption and pollutant adhesion on insulation surfaces.

B. Operational Practices and Monitoring

- Implement **partial discharge detection systems** in substations and cable networks to identify early signs of insulation deterioration due to corona or treeing.
- Establish **preventive maintenance schedules** based on environmental severity indices (pollution class, humidity, UV exposure) and insulation age.
- Improve cable laying techniques in underground and wet environments to minimize mechanical defects and reduce water tree initiation points.

C. Standards and Quality Assurance

- Advocate for the adoption of international testing protocols (e.g., IEC 60587, ASTM D2303) in local utilities for tracking and erosion resistance evaluation.
- Encourage utilities to perform accelerated aging and thermal cycling tests on new insulator batches before field deployment.

D. Research and Development

- Promote further experimental research on nano-dielectrics and smart materials with self-healing or self-cleaning capabilities.
- Conduct field-based aging studies that correlate tracking patterns with climatic zones, pollutant types, and operational load profiles.
- Explore the integration of AI-driven diagnostic tools for real-time anomaly detection in high-voltage insulation systems.

References

1. Ghosh, D., & Khastgir, D. (2018). Degradation and Stability of Polymeric High-Voltage Insulators and Prediction of Their Service Life through Environmental and Accelerated Aging Processes. ACS Omega, 3(9), 11317–11330.
2. Hackam, R. (1999). *Outdoor HV composite polymeric insulators*. IEEE Transactions on Dielectrics and Electrical Insulation, 6(5), 557–585.
3. Wang, H., Zhang, Z., & Li, J. (2021). Surface tracking characteristics of polymeric insulators under salt-fog and wet contamination. IEEE Access, 9, 12403–12412.

4. Anghelescu, L., Handra, A. D., & Diaconu, B. M. (2025). Degradation pathways of electrical cable insulation: A review of aging mechanisms and fire hazards. *Fire*, *8*(10), 397.
5. Chrzan, K., & Rosiński, M. (2016). *Failure analysis of composite insulators in power networks*. Energies, 9(3), 204.
6. Sundararajan, R., Gorur, R. S., & El-Hag, A. H. (2004). *Material characterization of polymeric housing materials for outdoor insulators*. IEEE Transactions on Dielectrics and Electrical Insulation, 11(2), 348–361.
7. International Electrotechnical Commission (IEC). (2022). *IEC 60587:2022: Electrical insulating materials used under severe ambient conditions—Test methods for evaluating resistance to tracking and erosion*. Geneva, Switzerland: IEC.
8. Alabi, A. S., Popoola, P. A., Popoola, O. M., Umaru, O. B., & Joshua, G. (2026). Overview on the recent technique on the evaluation of insulation of the polymer micro-and nanocomposite materials. In *Polymer Micro and Nanocomposites for High Voltage Insulation* (pp. 195-219). Elsevier.
9. Karim, A. M., Karal, Ö., & Çelebi, F. V. (2018, July). A new automatic epilepsy serious detection method by using deep learning based on discrete wavelet transform. In *Proceedings of the 3rd International Conference on Engineering Technology and Applied Sciences (ICETAS)* (Vol. 4, pp. 15-18).
10. Ramadan, Nizar, and Imad Omara Shebani Etomi. "Impact of Pollution on Leakage Current in Polymeric Insulators: Time and Frequency Domain Analysis." *Surman Journal of Science and Technology* 6.2 (2024): 093-102.
11. Madi, Ali Mustafa, et al. "Biodegradation of Polymeric Insulators Used in Electrical power." *Surman Journal of Science and Technology* 5.1 (2023): 031-040.
12. Madi, Ali Mustafa, et al. "Surface Degradation of Polymer Insulator under Ultraviolet Stress." *Int. J. Eng. Res. & Technol* 5.2 (2016): 315-319.
13. Tavakol, N., Teimoortashloo, M., & Esmaeelzadeh, F. (2025). Modeling and Analysis of Surface Contamination in Ceramic and Polymeric Insulators Using Partial Discharge Signal Characteristics. *Journal of Resource Management and Decision Engineering*, *4*(1), 1-13.
14. Guwaeder, Abdulmunim, et al. "Modeling monthly insolation data." *Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XVII*. Vol. 11495. SPIE, 2020.
15. Madi, Ali, et al. "Surface tracking on polymeric insulators used in electrical transmission lines." *Indonesian Journal of Electrical Engineering and Computer Science* 3.3 (2016): 639-645.
16. Jin, J. (2025, October). Research Progress on Aging of Insulation Materials of Power Equipment under Extreme Temperature Cycles. In *Proceedings of the 2025 2nd International Conference on Electrical Engineering and Intelligent Control (EEIC 2025)* (p. 183). Springer Nature.
17. Dalla, L. B., Karal, Ö., Mhamed, E. S., & Alsharif, A. (2026). An IoT-Enabled, THD-Based Fault Detection and Predictive Maintenance Framework for Solar

PV Systems in Harsh Climates: Integrating DFT and Machine Learning for Enhanced Performance and Resilience. *Wadi Alshatti University Journal of Pure and Applied Sciences*, 41-55.

18. Mavrikakis, N., & Siderakis, K. (2026). Condition Assessment of Field-Aged Composite Insulators Following Incidents of Insulator Flashunder. *Energies*, *19*(10), 2325.

19. EL-sseid M, Abdulgader A, Ben Dalla LOF, Elzer R, Abdussalam A, Ali T,Ali F, Alarafi M, Agaal A, Salih A.(2026). The novelty based on Energy Management Technologies for Integrated Microgrid frameworks. Comprehensive Journal of Science, 11(42), 163-174. https://doi.org/10.65405/f9606j11

20. Ramadhan, H. R. S. R., Osman, M., Ben-Dalla, L., Rashid, T., Albaraesi, M., EL-sseid, M. A. M., & Alnnale, T. (2025). A New Approach of the Machine Learning Framework Integrating Policy Design to Predict Renewable Electricity Penetration in Resource-Constrained Settings. Comprehensive Journal of Science, 10(Supplement 38), 2929-2950.

21. Danisman, K. E. N. A. N., Dalkiran, I., & Celebi, F. V. (2006). Design of a high precision temperature measurement system based on artificial neural network for different thermocouple types. *Measurement*, *39*(8), 695-700.

22. Ghunem, Refat. A Study of the Erosion Mechanisms of Silicone Rubber Housing Composites. Diss. University of Waterloo, 2014.

23. El-Khozondar, Hala J., Yasser F. Nassar, Rifa J. El-Khozondar, Mohamed Elnaggar, Wael A. Salah, Sassi Rekik, Monaem Elmnifi, Mohamed Khaleel, and Llahm Omar Ben Dalla. "Analysis of a grid/wind/hydrogen hybrid energy system for producing electricity, vehicle fuel and freshwater for Gaza Strip-Palestine." *Fuel* 428 (2027): 140358.

24. Madi, Ali Mustafa, et al. "Degradation of Polymers Insulators used in Electrical Transmission Lines under the Rate of Bond Breaking." *Surman Journal of Science and Technology* 6.1 (2024): 016-028.

25. Syakur A, Hermawan, Sarjiya, Hamzah Berahim. Analyze of Hydrophobic Characteristics of Surface Material Based on The Value of THD Leakage Current. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2009; 7(2):109-118.

26. Madi, Ali Mustafa, et al. "(Design Criteria for Silicone Rubber Insulators (Composite Insulator." *Surman Journal of Science and Technology* 2.3 (2020): 006-001.

27. Alsharif, A., Dalla, L. B., Essgaer, M., Ahmed, A. A., Rashid, T. A., & Alnnale, T. (2026). The Water-Energy-Food-Ecosystems (WEFE) Nexus in Libya: Challenges, Opportunities, and Integrated Governance Mechanisms. Al-Farooq Journal of Sciences, 2(Supplement 3), 1187-1198.

28. Brady J, Thermographer LI. Corona and Tracking Conditions in Metal-clad Switchgear Case Studies. *Brady Infrared Inspections*. 2006.

29. Begovic MM, editor. Electrical Transmission Systems and Smart Grids: Selected Entries from the Encyclopedia of Sustainability Science and Technology. Springer Science & Business Media; 2012 Dec 12.

30. Arora R, Mosch W. High voltage and electrical insulation engineering. John Wiley & Sons; 2011 Aug 4.

31. Ben Dalla. LOF, Asma Farhat MOHAMMED, ÖMER KARAL , Mansour Essgaer, Hala J. EL-KHOZONDAR, Yasser Fathi Nassar.(2026).Predictive Modeling of Daily Performance Ratio and Fault Classification in Photovoltaic Systems: A Comparative Deep Learning Study Using Real-World IoT Telemetry in a semi-arid desert climate.Trend and Advanced Studies in Engineering.Publisher's Certification Number: 72273.ISBN: 978-625-8839-39-5. All Sciences Academy,https://www.allsciencesacademy.com/_files/ugd/13252f_9af950f099ca4c9d93d837f5dc82e130.pdf

32. Alsharif, A., Ibrahim, A. A., Waheshi, Y. A. A., Alsharif, M., Alhoudier, T. E., Esmail, E. M. A., & Dalla, L. O. F. B. (2025). An Analysis of Power Sector Investment by Technology in the Middle East and North Africa. African Journal of Academic Publishing in Science and Technology (AJAPST), 1(4), 25-39.

33. Dalla, L. O. B., KARAL, Ö., Degirmenci, A., CANBOLAT, H., ÇELEBI, F. V., & Nassar, Y. F. (2026). A Novel Hybrid Optimization Framework for Renewable Energy Investment in Hot Arid Regions: Integrating Time-Series Forecasting and AI-Driven Algorithms for Algeria's Grid-Export Strategy. Fezzan University Scientific Journal, 62-76.

34. Madi, Ali Mustafa, Yadong He, and Lilong Jiang. "Design and testing of an improved profile for silicone rubber composite insulators." *IEEE Transactions on Dielectrics and Electrical Insulation* 24.5 (2017): 2930-2936.