Engineering and Technology Journal e-ISSN: 2456-3358

Volume 11 Issue 07 July-2026, Page No.-10912-10920

DOI: 10.47191/etj/v11i07.14, I.F. – 8.595

A Study on Performance of Ageing High Voltage Polymer Insulators in AC Systems

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ABSTRACT: High voltage polymer composite insulators have become the preferred choice for transmission and distribution networks worldwide owing to their superior contamination flashover performance, lightweight construction, and inherent hydrophobic surface properties. However, as the installed insulators progressively matures beyond its design life, understanding the cumulative impact of ageing on their electrical and mechanical performance has emerged as a critical concern for transmission system operators and insulation engineers globally. This paper presents an analysis examining how ageing affects the performance of high voltage polymer composite insulators across multiple voltage classes, diverse environmental conditions, and a wide range of service durations. The root causes of ageing and their consequences on electrical and mechanical performance are studied. key strengths, weaknesses, and vulnerabilities of polymer composite insulators are discussed and possible preventive measures are presented providing a clear agenda for future investigation.

KEYWORDS: High Voltage Insulators, Polymer Insulators, Ageing, Insulator Performance, Degradation, Condition Assessment.

I. INTRODUCTION

The uninterrupted and consistent performance of high voltage power transmission lines is entirely dependent on the functionality of the line insulators, whose primary function is to provide insulation between the energized transmission lines and the ground, as well as provide mechanical strength to the transmission lines[1]. Insulators are therefore critical components of the transmission system, and any degradation in their performance directly compromises the operational safety and reliability of the entire power network[2]. Porcelain insulators have traditionally been preferred in these applications due to their superior chemical stability, robust dielectric characteristics, and established mechanical durability in varied environmental settings[3][4]. However, the limitations associated with these conventional insulators including their considerable weight, hydrophilic surface nature, susceptibility to pollution-induced flashover, and intensive maintenance requirements, particularly in coastal and industrially polluted environments prompted a paradigm shift toward the development and adoption of polymer insulators. Polymer insulators, commercially introduced in the 1970s, are composed of a fiber reinforced plastic core that provides primary mechanical strength, a polymeric housing of silicone rubber or EPDM that delivers electrical insulation and environmental protection, and metal end fittings that ensure robust mechanical connection to the transmission line. This composite structure imparts several highly desirable characteristics, including superior hydrophobicity, excellent pollution flashover performance, high strength to weight ratio, resistance to vandalism, and ease of installation and handling, all of which have driven their rapidly increasing adoption in modern high voltage transmission networks across diverse climatic and environmental conditions. Furthermore, the inherent ability of silicone rubber to recover hydrophobicity following exposure to contamination through the migration of low-molecular-weight silicone molecules to the surface distinguishes polymer insulators significantly from their ceramic counterparts, offering a self cleaning mechanism that substantially reduces maintenance interventions and operational costs [5][6]. Despite these compelling advantages, the long term field performance of polymer insulators is significantly challenged by progressive ageing under the combined influence of electrical, environmental, and mechanical stresses Polymer insulators experience simultaneous degradation stressors in field service: UV radiation, thermal cycling, contamination, mechanical loading, and continuous electrical stress [7][8]. Their interaction produces ageing consequences more complex and severe than any single stressor studied in isolation [9]. Leakage current (LC) escalation, hydrophobicity loss, flashover voltage reduction, and partial discharge (PD) activity are the sign of electrical degradation[10]. Mechanical degradation often initially invisible can produce shed fracture, core rod decay-like failure, and conductor drop [11]. Critically, mechanical and electrical degradation are not independent: surface cracking enables moisture ingress, electric field intensification drives material erosion, and core rod chemical hydrolysis simultaneously destroys insulation integrity and structural strength [12].

The present review consolidates the available research on ageing of high voltage polymer insulators, critically analyze their electrical and mechanical performance, and identifies key strengths, weaknesses, and corrective measures to support safe and reliable insulator asset management.

II. AGEING MECHANISMS: CLASSIFICATION AND OVERVIEW

A. Electrical Ageing

Electrical ageing encompasses surface and internal degradation driven by the energized field principally corona discharge at end fittings, dry band arcing along contaminated surfaces, and internal PD at manufacturing defects or interface voids.[13]established that corona under fog is substantially more damaging than dry air corona the AC corona current pulse pattern shifts markedly under fog exposure, and acidic fog (pH 3.3) produces the most severe surface degradation through nitric acid formation on the shed surface. This acid product is not merely a surface contaminant it diffuses toward the FRP core rod, initiating the glass fiber epoxy interface hydrolysis that underlies decay-like fracture [14]. Internal electrical ageing initiated by manufacturing voids is the most severe pathway. [12] documented that sustained interfacial discharge at the sheath-core boundary drives progressive electro erosion of the FRP rod, that reduce elevate flashover risk. Positive feedback is established discharge generates heat and acid, degrading the interface further and enabling greater moisture ingress, which intensifies discharge [15]**.** The four stage progression model of [15] initial moisture accumulation, slight thermal rise, active PD, and flashover path alteration with imminent fracture is the most comprehensive framework for understanding how internal electrical ageing leads to catastrophic mechanical failure. [16]replicated this chain experimentally by applying combined mechanical pre-stress, nitric acid, and moisture to composite insulators, reproducing the same macroscopic appearance as field-failed decay-like specimens and confirming leakage current escalation and IR detected hotspots as the earliest co-occurring warning signals. Non-uniform electric field distribution along the insulator string is an inherent feature of composite insulator design with pronounced ageing consequences. [17] demonstrated through FEM that the electric field concentrates at end fittings and shank regions, creating zones of elevated corona risk.

B. Environmental Ageing

Environmental ageing is the dominant degradation pathway for most field-deployed polymer insulators, encompassing UV radiation, thermal cycling, contamination accumulation, and wetting events. UV radiation causes photo oxidative chain scission of the SiR polydimethylsiloxane (PDMS) backbone, depleting the low molecular weight (LMW) silicone fluid that migrates to the surface to confer hydrophobicity[18]. Even one to two years of outdoor-equivalent UV exposure measurably raises leakage current under medium pollution severity, confirming UV radiation as a standalone driver of surface resistance reduction. [7]further showed that under pure dry arid-climate thermal ageing without a wetting component, LC and flashover voltage remain stable establishing that moisture is the necessary activating factor that converts thermal-induced material changes into measurable electrical degradation. Surface contamination characterized by ESDD and NSDD interacts with UV induced hydrophobicity loss in a compounding manner. [19] demonstrated through 23 months of real time online LC monitoring on a 20 kV tropical network that pollution accumulates during the dry season creating a period of high latent electrical risk, then becomes highly conductive upon first wetting at the rainy season onset, causing dramatic LC spikes. [20] and [21] independently confirmed that NSDD (non-soluble deposits such as kaolin and dust) is more electrically damaging than ESDD alone, physically blocking SiR's LMW hydrophobicity recovery mechanism and sustaining elevated surface conductivity even after rainfall. [22] demonstrated through controlled saline deposition testing that cold fog is electrically more dangerous than rainfall at the same wetting rate stronger moisture absorption forms a lower-resistance contamination layer producing higher discharge current and lower flashover voltage, while rainfall simultaneously provides partial natural self cleaning with ESDD reduction of up to 34.7%. The harshest environmental ageing conditions in this review are those combining coastal salt spray with desert UV and sandstorm abrasion. [23] studied 380 kV SiR insulators after ten years of service in Dhahran, Saudi Arabia, finding hydrophobicity had degraded from HC1 to HC5, with wet flashover withstand reduced by up to 30%. [24] assessed 230 kV composite insulators after 20 years of coastal Arabian Gulf service and found complete hydrophobicity loss (HC6) and heavy corona throughout service, yet insulators retained acceptable electrical withstand demonstrating the inherent resilience of SiR design even under severe prolonged ageing.

C. Mechanical Ageing

Mechanical ageing encompasses physical shed damage, surface cracking of the housing, and FRP core rod degradation under sustained and dynamic mechanical loads. [25] quantified the electrical consequence of shed damage simulating bird-peck incidents across 35 kV, 110 kV, and 220 kV, finding that even 6% shed area loss measurably reduces pollution flashover voltage. The reduction exceeds the proportional geometric loss of creepage distance because electric field distortion at the damage site acts as a compounding factor. Lower voltage class insulators suffer proportionally greater electrical degradation from equivalent damage due to their higher creepage-to-arc-distance ratio. [22] showed that wind speeds above 12 m/s physically deform insulator sheds by up to 45° in twist angle, disrupting the creepage distance geometry and directly modifying electric field distribution and pollution accumulation patterns. The IEEE Task Force Report on brittle fracture in nonceramic insulators highlighted that mechanical ageing significantly contributes to the deterioration of polymer insulators. Continuous mechanical stresses such as conductor vibration, bending, excessive loading, and improper handling can initiate microcracks and damage the sheath or end-fitting seals. These defects allow moisture ingress into the fiberglass reinforced polymer (FRP) core, leading to stress corrosion cracking and eventual brittle fracture. The study emphasized that mechanical ageing combined with environmental exposure accelerates the loss of both mechanical and electrical reliability of polymer insulators [26].

D. Combined and Multi-Stress Ageing

Real field insulators experience simultaneous UV, thermal, contamination, mechanical, and electrical stress yet most laboratory studies apply only one or two stressors. [9]applied a combined multi-stress protocol (temperature, humidity, electrical stress) to HTV SiR insulators and demonstrated that LC increases in a non-linear, self accelerating manner a degradation rate impossible to replicate through single stress studies and confirming that isolated stressor experiments alone cannot adequately characterize real-field ageing. [27] showed that combined UV and contaminant solution ageing over just 100 hours approximately doubled LC under clean fog conditions and created near flashover risk under combined salt-kaolin pollution at operating voltage confirming the multiplicative interaction between UV induced surface degradation and pollution loading. The most catastrophic combined stress scenario is decay like fracture, in which moisture ingress through end fitting seals, PD at the rod housing interface, and acid attack of the FRP rod act in concert to destroy both electrical insulation and mechanical structural integrity simultaneously. [28]analyzed a 400 kV composite insulator that failed by decay-like fracture and demonstrated through COMSOL FEM that the root cause was inadequate corona ring design allowing the electric field on the SiR sheath to exceed 4.2 kV/cm at normal operating voltage sustaining continuous discharges that initiated the full degradation cascade. This establishes that electric field management, not pollution severity, is the dominant factor in preventing decay like fracture.

III. IMPACT ON ELECTRICAL PERFORMANCE

A. Leakage Current Behaviour and Harmonic Analysis

Leakage current monitoring is the most universally applicable and sensitive electrical indicator of ageing state. [29]demonstrated that aged SiR insulators consistently show higher LC under every identical environmental condition, and that combined surface pollution and salt fog produce a multiplicative effect on LC escalation. Surface pollution has a greater influence on LC than atmospheric pollution alone. [30] confirmed through systematic LC and THD testing on alternating-shed polymer insulators that water contamination produces the highest LC under all conditions, and that hydrophobic silicone oil coating reduces both LC and THD directly demonstrating that hydrophobicity restoration suppresses the electrical degradation pathway. The complete LC ageing lifecycle was most comprehensively documented by [31], who tracked LC from initial phase through an intermediate dry band phase to end of life on five types of 20 kV coastal SiR insulators with 3 to 9 years of field service. The 3rd harmonic content of the LC waveform rises sharply at the dry band formation stage providing a quantitative ageing timeline and roadmap for condition monitoring system design and replacement thresholds. [21]extended this by mapping LC harmonic signatures to surface condition states: odd harmonic prominence (3rd, 5th, 7th) indicates dry-band arcing; near sinusoidal waveforms at extreme humidity indicate uniformly wet surface approaching flashover; and a pre-flashover LC surge is a detectable electrical warning signal that precedes flashover. An important diagnostic nuance was identified independently by [20]and confirmed by [21] that LC magnitude and THD behave inversely as degradation severity increases. At higher contamination and advanced ageing, the fundamental current component dominates the waveform such that THD expressed as a percentage actually decreases and electrical hazard increases. THD alone is therefore a potentially misleading diagnostic indicator and must always be interpreted alongside absolute LC magnitude.

B. Flashover and withstand voltage degradation

Pollution flashover voltage declines progressively with ageing and is strongly influenced by insulator geometry. [10]found that flashover voltage declines non linearly with age and pollution severity in 33 kV field aged SiR insulators, with 15 year specimens showing substantially reduced flashover margins versus new insulators. Insulator geometry leakage distance and form factor significantly modifies the rate of FV degradation, with higher specific creepage distance providing greater resilience. A counterintuitive finding of major practical importance was reported by [32] It states that the aged composite insulators from an active Bulgarian 110 kV transmission network showed flashover voltages notably higher than new insulators, yet simultaneously demonstrated corona discharge onset at much lower voltages under wet conditions. New insulators showed zero corona at any tested voltage. This result supported by the broader comparative testing of [33] using probabilistic IEC 60060-1 impulse methods establishes that withstand voltage testing alone is an inadequate and potentially misleading diagnostic tool for aged polymer insulators. An insulator may pass a standardized withstand test whilst already showing corona activity signaling progressive surface degradation. Corona onset voltage under wet conditions is the more sensitive early indicator. The relationship between mechanical shed damage and flashover voltage reduction was quantified by [25] it states that even 6% shed area loss reduces pollution flashover voltage, with the reduction disproportionate to the geometric creepage loss due to electric field distortion at damage sites. At 25 to 28% damage reaching the core rod, the maximum FV reduction was observed establishing this as the critical damage threshold. [7] reported that during dry flashover voltage testing on thermally aged SiR, a shed puncture was detected in one specimen due to pre existing manufacturing voids intensified by electric field concentration confirming that combined electrical stress testing during condition assessment can reveal hidden defects invisible to visual inspection.

C. Hydrophobicity Loss and Electric Field Intensification

Hydrophobicity is the primary electrical protection mechanism of SiR composite insulators. Its progressive loss is therefore the most consequential electrical performance degradation pathway. [23] provided the most analytically rigorous quantification, FEM simulation of the 380 kV field-aged insulator showed the transition from HC1 to HC5 produces up to 1200% intensification of the surface electric field in localized zones, with peak fields in shank regions exceeding the corona inception threshold. This result reframes hydrophobicity loss from a surface chemistry concern to an electric field engineering problem of urgent operational significance. [34]The study demonstrated that hydrophobicity loss and non-uniform pollution accumulation (ESDD/NSDD) jointly intensify surface electric field stress in field-aged 380 kv polymer insulators. Higher contamination on lower sheds increased surface conductivity, leading to localized electric field enhancement and accelerated surface degradation, as confirmed through COMSOL simulations and microscopic analysis. The fundamental material level driver of hydrophobicity loss differs profoundly between SiR and EPDM. [35] compared EPDM and HTV SiR insulators after 17 years of coastal service and found EPDM reached wettability class 6 (hydrophilic) while SiR retained wettability class 2 (hydrophobic) despite the EPDM insulator operating at a site with lower pollution severity. meaning material selection governs long-term electrical reliability more decisively than environmental exposure alone. A remarkable counterpoint was established by [36], who studied 70 kV SiR insulators after 30 years in a severe tropical-volcanic environment and found hydrophobicity class HC1 retained despite visible sheath cracking demonstrating SiR's LMW self-recovery mechanism can maintain electrical protection well beyond conventional design life under volcanic precipitation conditions. This contrasts sharply with [23] finding of HC5 after only 10 years in a coastal desert environment, confirming that environment type and severity not ageing duration alone govern the rate of hydrophobicity degradation.

D. Partial Discharge and Internal Electrical Degradation

PD activity is universally identified as the core electrical degradation mechanism driving decay like fracture yet it is simultaneously the most diagnostically neglected parameter. [16]documented PD initiated from manufacturing voids of 2 to 5 mm within 500 kV class insulator rubber sheaths as the primary driver of abnormal heating and progressive interface failure. As voids expanded into the skirt housing interface, insulation distance was directly reduced in a self-reinforcing progression. [37]reproduced this process experimentally by combined mechanical pre stress, nitric acid, moisture, and interfacial discharge drove a steep continuous rise in surface LC throughout the discharge-ageing phase, with localized rod surface temperatures reaching extreme values indicating incipient thermal breakdown all directly preceding catastrophic mechanical failure of the core rod. At the rod material level, [14]demonstrated through combined thermal and acidic ageing of FRP core rods simulating PD generated conditions that water diffusion test (WDT) leakage current increases markedly for combined thermal acid aged samples, with longitudinal voids formed by epoxy degradation becoming direct conduction paths. Inclined plane tracking time to track decreased progressively with ageing severity, the most severely aged samples lost all tracking resistance within seconds representing complete electrical breakdown. [38] independently confirmed that surface discharge under salt fog on FRP rods erodes the epoxy matrix and exposes glass fibers, with the sheathed region showing no such degradation directly demonstrating that sheath integrity is the electrical and mechanical protection boundary whose failure initiates irreversible rod degradation.

E. Dielectric Property Changes

Beyond surface electrical parameters, ageing also modifies bulk dielectric properties. [10] The study observed that ageing causes a noticeable increase in dielectric dissipation factor (tan δ) and capacitance of polymeric insulators, indicating deterioration of dielectric performance. The rise in tan δ reflects higher dielectric losses and increased energy dissipation within the insulation material due to ageing induced polarization effects. Simultaneously, capacitance increased because ageing promoted the formation of polar groups such as hydroxyl and carboxyl molecules, along with moisture ingress into the polymer matrix. These polar substances enhanced polarization currents and electrical energy storage within the material, resulting in increased capacitance and conductance, ultimately reducing the insulation quality and dielectric strength of the insulator. [39] confirmed through 2000 hour tracking wheel testing that tan δ rises to 5 to 20 times its virgin value with ageing, while capacitance remains stable confirming that tan δ reflects bulk dielectric deterioration whilst capacitance reflects geometric structural preservation, and that both parameters together provide a more complete picture of dielectric ageing state than either alone.

IV. ADDITIONAL FACTORS

A. Shed Cracking and Creepage Distance Reduction

Physical damage to the insulator shed reduces the creepage distance available to resist pollution flashover through both geometric path shortening and electric field distortion. [25]established that the flashover voltage reduction from shed damage exceeds the proportional creepage loss, confirming field distortion as a compounding factor. The creepage to arc distance ratio (L/H) is the governing electrical parameter: lower voltage class insulators with inherently higher L/H ratios suffer disproportionately greater FV reduction from equivalent physical damage. Wind-induced shed deformation above 12 m/s [22]and UV-induced surface cracking [35] represent real field mechanical pathways to electrical performance degradation that operate continuously throughout service life. Surface cracking is the most electrically consequential mechanical surface degradation feature. [35] documented EPDM surface cracking up to 30 µm depth after 17 years of coastal service, with crack channels retaining hydrophilic pollutants and ageing by products that sustained elevated surface conductivity. [36] found that in 30 year old SiR insulators, sheath cracking near the energized end produced higher leakage current directly attributable to those crack sites, whilst bulk hydrophobicity remained HC1 establishing that local mechanical cracking is the primary electrical risk driver at end of life for SiR insulators, not bulk material degradation.

B. Corona Ring Design and End-Fitting Electric Field Stress

The study demonstrated that corona ring geometry and installation location strongly influence electric field stress distribution on 380 kV insulators. Larger corona ring and tube diameters reduced electric field concentration at critical regions, while an optimum mounting height provided effective field regulation, minimized corona discharge activity, and reduced radio interference[40]. [17] demonstrated through FEM that incorrectly positioned corona rings can amplify rather than reduce local field stress at end fittings actively accelerating ageing at the zones most vulnerable to decay like fracture initiation. [28]demonstrated through COMSOL FEM with BOBYQA optimization that an improved corona ring geometry raised the corona onset voltage and reduced the HV triple junction field. No international standard currently specifies corona ring positioning or design criteria to prevent decay like fracture, representing one of the most critical regulatory gaps in the standards framework for HV composite insulators.

C. Material Type: SiR vs EPDM vs Epoxy Resin

The housing material is the most fundamental determinant of long term electrical performance under field ageing. SiR in HTV and forms consistently outperforms EPDM and epoxy resin through its hydrophobicity transfer mechanism: LMW silicone fluid chains migrate from bulk to surface, continuously replenishing hydrophobicity after contamination or discharge events. [36] 30 year field study demonstrated the remarkable durability of this mechanism HC1 retained despite severe volcanic-tropical conditions confirming SiR's self recovery can maintain electrical protection well beyond conventional design life. [24]'s 20 year assessment of 230 kV coastal insulators with complete HC6 loss yet acceptable withstand performance further underlines SiR composite design resilience under sustained severe exposure. In direct comparison, [35] established definitively that EPDM reaches wettability class 6 (hydrophilic high flashover risk) after 17 years of coastal service while HTV SiR operating at higher pollution severity retained wettability class 2 (hydrophobic low risk). The LC implications are directly quantifiable through [41] systematic comparison, SiR consistently produced lower LC than epoxy resin insulators under all dry and wet conditions at 20 kV due to higher intrinsic hydrophobicity. Additionally, [41] demonstrated that shed geometry is an independent electrical performance variable: same shed (longer creepage path) configurations produce lower LC than different-shed designs under equivalent pollution loading establishing that mechanical design and material selection must be jointly optimized in polluted environment procurement decisions.

V. KEY OBSERVATIONS

Acidic fog corona is the most severe degradation factor as it generates nitric acid that directly attacks the FRP core rod, while internal manufacturing voids initiate partial discharge activity causing progressive thermal and interfacial degradation.

UV induced depletion of LMW silicone destroys hydrophobicity recovery, and NSDD accumulation is more electrically damaging than ESDD as it sustains elevated surface conductivity even after rainfall.

Shed area loss reduces flashover voltage disproportionately due to electric field distortion, with lower voltage class insulators most vulnerable, and wind-induced shed deformation further causing non-uniform pollution accumulation.

Leakage current increases non-linearly under combined field stresses, and decay-like fracture the most catastrophic failure mode is primarily driven by moisture ingress through end-fitting seals combined with sustained electric field stress.

LC magnitude paired with THD is the most sensitive condition monitoring tool, though THD alone is misleading at advanced ageing stages as it decreases despite escalating electrical hazard.

Aged insulators may pass dry withstand voltage tests while already exhibiting corona onset under wet conditions, confirming that dry withstand testing alone is an insufficient and potentially dangerous diagnostic.

Hydrophobicity loss causes up to localized electric field intensification, with HTV silicone rubber decisively outperforming EPDM in long-term hydrophobicity retention under severe environmental exposure.

tan δ rising to higher values compared to its virgin sample value alongside increasing capacitance together provides the most reliable indicator of internal bulk dielectric deterioration that surface monitoring alone cannot detect.

VI. PREVENTIVE MEASURES AND RECOMMENDATIONS

Corona rings must be optimally designed using FEM simulations to suppress electric field concentration at end fittings, mandatory preservice partial discharge testing should eliminate manufacturing voids, and end-fitting seal integrity must be rigorously verified to prevent moisture ingress initiating decay-like fracture.

Periodic hydrophobicity assessment using HC classification should guide maintenance intervals, scheduled silicone oil recoating should replenish depleted LMW silicone in high UV environments, and contamination severity classification must explicitly account for NSDD alongside ESDD to determine appropriate creepage distance selection.

Quantitative shed damage tolerance thresholds must be established for each voltage class, regular visual inspection should ensure prompt removal of insulators exceeding damage limits, and aerodynamically stable shed profiles must be specified in high wind speed locations to minimize non-uniform pollution accumulation.

Insulator qualification must transition from single-stress to combined multi-stress ageing protocols reflecting real field conditions, and enhanced end-fitting sealing systems must be specified as a critical engineering parameter to suppress decay-like fracture initiation under combined stress exposure.

Real time online LC monitoring must be deployed in polluted and coastal environments, with threshold based alarms configured on combined LC magnitude and THD criteria, as THD interpreted in isolation is actively misleading at advanced ageing stages.

Wet condition corona onset voltage testing must be mandatorily incorporated alongside dry withstand voltage testing in condition assessment frameworks, and international standards bodies should be urged to formalize this requirement to close the existing critical diagnostic gap.

HTV silicone rubber must be mandatorily specified in polluted, coastal, and high UV environments, with procurement policies explicitly restricting EPDM use, and field hydrophobicity monitoring should flag insulators reaching HC5 for immediate maintenance or replacement.

tan δ and capacitance must be incorporated as mandatory bulk ageing indicators in periodic condition assessment alongside surface-based parameters, with baseline values recorded at installation to enable meaningful trending and threshold-based replacement decisions throughout service life.

VII. CONCLUSIONS

This review has examined the ageing behavior of high voltage polymer composite insulators under electrical, environmental, mechanical, and multi stress conditions across diverse climatic environments and voltage classes. The findings confirm that long term reliability of polymer composite insulators is fundamentally challenged by progressive and interacting degradation mechanisms. Acidic fog corona, UV induced hydrophobicity loss, NSDD accumulation, shed damage, and moisture ingress through end fitting seals collectively drive electrical and mechanical deterioration in a non-linear, self-accelerating manner that single-stress laboratory studies and conventional diagnostic tools consistently fail to capture. Most critically, decay like fracture driven by combined moisture ingress and sustained electric field stress represents a catastrophic and largely invisible failure mode that current inspection and standards frameworks are inadequately equipped to prevent or detect. Moreover, withstand voltage testing in both dry and wet conditions can be very tool to evaluate ageing condition, regular electric field stress assessment enables to check the effectiveness of corona ring. Addressing these challenges demands a shift from periodic visual inspection toward continuous multi-parameter condition monitoring integrating leakage current, tan δ, hydrophobicity assessment, and wet condition corona onset voltage measurement, supported by multi-stress qualification protocols and enhanced end-fitting sealing as engineering necessities for safe long-term insulator performance

ACKNOWLEDGMENT

The author sincerely acknowledges Electrical Engg. Department, FoTE**,** The Maharaja Sayajirao University of Vadodara, India for its continuous academic support and encouragement. The author also extends sincere thanks to the Electrical Research and Development Association (ERDA) Vadodara, India for its expert guidance and the provision of an excellent research environment, all of which substantially contributed to the successful completion of this review article.

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