BRIDGE: The Multidisciplinary Research Portal
Vol. 3, No. 2 (2025), pp. 318-325 | p-ISSN: 3025-6585, e-ISSN: 3025-3640
https://jurnal.sttnlampung.ac.id/index.php/bridge

Thermal and Environmental Degradation of Low-Voltage Cable Insulation for Predictive Maintenance Applications

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Article History: Received: June, 28th 2025; Accepted: August, 7st 2025; Published: August, 31th 2025

ABSTRACT

Low-voltage cable insulation degradation poses a significant risk to the reliability and safety of power distribution systems, particularly under combined thermal and environmental stress conditions. This study investigates the dominant degradation mechanisms affecting low-voltage cable insulation in distribution networks, using field measurements at the PR009 transformer substation as a representative case. The analysis focuses on the interaction between thermal overloading, electrical stress, moisture ingress, and environmental contamination, and their cumulative impact on insulation performance. A quantitative experimental field approach was employed, integrating insulation resistance testing, dielectric loss (tan δ) analysis, partial discharge evaluation, and theoretical modeling of electrical and thermal behavior. The results indicate that excessive current loading and phase imbalance lead to elevated conductor temperatures, intensifying thermal stress and accelerating insulation aging. Intrinsic electrical breakdown, streamer-induced partial discharge activity, dielectric losses, and limited heat dissipation were identified as primary contributors to degradation. Environmental factors, particularly high humidity and acidic soil conditions, were found to further exacerbate chemical and mechanical deterioration of polymeric insulation materials. The findings highlight the effectiveness of condition-based diagnostic techniques for early detection of insulation deterioration and support the implementation of predictive maintenance strategies. This study provides practical insights for utilities and asset managers to enhance service reliability, reduce unplanned outages, and optimize the lifecycle management of low-voltage distribution cables under realistic operating and environmental conditions.

Keywords: *low-voltage cables; insulation degradation; thermal stress; partial discharge; predictive maintenance*

INTRODUCTION

In the modern era, the increasing demand for electricity has made safety and reliability in power distribution systems a primary concern. Both urban and rural communities depend on the stability of electrical supply for lighting and household appliances. However, serious risks may arise when electrical installations are inadequately designed or maintained. One of the most critical technical issues is the degradation of low-voltage cable insulation due to thermal stress a phenomenon that can lead to current leakage, insulation failure, and, in severe cases, fires (Mustafa et al., 2020).

Recent studies have focused extensively on non-destructive methods for detecting insulation deterioration under thermal stress. Mustafa et al. (2021) investigated the effects of heating on the dielectric behavior of CSPE/XLPE-based cables, noting that both tan δ and extended voltage response (EVR) exhibited significant changes with material aging; they found a strong correlation between tan δ and the decay voltage slope, suggesting the potential use of these parameters for in situ condition monitoring (Mustafa et al., 2019). Similarly, Paun et al. (2023) reported that extreme thermal cycling induced plasticizer diffusion and the formation of microcracks in PVC insulation layers, leading to notable mechanical degradation (Paun et al., 2023). In a related study, Domingos et al. (2025) proposed an evaluation method based on the progression of partial discharges in XLPE and EPR insulation, establishing a clear correlation between the level of insulation degradation and the rate of increase in partial discharge activity (Domingos et al., 2025).

These findings reinforce the understanding that non-destructive monitoring using dielectric parameters such as tan δ, EVR, and partial discharge measurements is highly effective for the early detection of insulation degradation. Such approaches allow timely preventive interventions, mitigate the risk of distribution system failures, and provide a basis for more reliable insulation lifetime estimations (Kruizinga, 2017). This is of paramount importance not only for designers and manufacturers of electrical equipment but also for consumers and electricity distribution service providers, including entities such as CV. Bumi Waras Lampung.

In practice, the low-voltage distribution network in the operational area of CV. Bumi Waras Lampung has shown evident signs of insulation degradation particularly at transformer substation PR 009 manifesting in damaged and cracked insulation, as well as frequent partial blackouts. Overheating caused by excessive current is suspected to be the primary factor contributing to insulation deterioration, which, if left unaddressed, could result in the further spread of damage and increased disruption to consumer electricity supply.

Against this backdrop, the present study aims to evaluate low-voltage cable insulation degradation due to thermal stress by conducting a material quality analysis on distribution substation cables at CV. Bumi Waras Lampung. The ultimate objective is to propose a condition monitoring methodology that is both practical and cost-effective, while supporting more responsible preventive maintenance planning (Afia et al., 2020).

METHODS

This study adopts a quantitative experimental field approach complemented by a comparative analysis of primary and secondary data. The research is focused on assessing the degradation of low-voltage cable insulation subjected to thermal stress within the distribution network managed by PT. PLN Rayon Sukadana. The study site was purposively selected to represent a range of load conditions and environmental factors that influence the service life of cable insulation.

Primary data were collected through direct in-field measurements using high-voltage test equipment, insulation resistance testers, and dielectric parameter analyzers capable of measuring *loss tangent* (*tan δ*) and *capacitance*. These diagnostic parameters have been widely recognized in recent studies as sensitive indicators for detecting early insulation aging (Domingos et al., 2025; Mustafa et al., 2021). Measurements were conducted under actual operating conditions to capture realistic performance profiles of cable insulation under thermal stress. Additionally, visual inspections were performed to identify surface defects such as cracking, embrittlement, and thermal erosion marks, which have been associated with accelerated dielectric breakdown (Paun et al., 2023).

Secondary data were obtained from PT. PLN's technical archives, including maintenance logs, outage reports, and historical cable replacement records. This dataset was further supported by an extensive literature review of peer-reviewed studies indexed in Scopus and Sinta, focusing on low-voltage cable degradation mechanisms, insulation material performance, and distribution system reliability.

The analysis compared the measured field data against established industrial benchmarks and permissible limits outlined in IEC 60502-1 and SPLN standards. Quantitative evaluation of insulation degradation was performed using the fundamental insulation resistance equation.

$$R_i = \frac{V}{I} \text{ ....(1)}$$

Where R_i is the insulation resistance in megaohms (MΩ), VVV is the applied test voltage in kilovolts (kV), and III is the leakage current in microamperes (μA). A significant reduction in R_i from nominal specifications is indicative of material deterioration. To estimate the statistical life expectancy of the cable under thermal stress, a *Weibull* distribution model was applied, as recommended in contemporary reliability engineering studies (Bal et al., 2024).

Failure mechanisms were further analyzed using the failure voltage versus logarithmic time curve, which classifies breakdown modes into intrinsic, electromechanical, streamer, thermal, and erosion types (Suraci et al., 2021). Understanding these modes is critical in developing targeted mitigation strategies, including scheduled cable replacement, load redistribution, and the integration of *online* condition monitoring systems. This multi-layered approach enhances both the operational reliability and the cost-efficiency of low-voltage distribution networks.

Through the integration of empirical measurements, statistical modeling, and cross-referencing with technical standards, this methodology provides a robust framework for diagnosing insulation health and guiding proactive maintenance planning. The outcomes are expected to contribute not only to asset management practices at PT. PLN but also to broader industry knowledge on extending the service life of low-voltage cable systems under thermal stress.

RESULTS AND DISCUSSION

The reliability of low-voltage (LV) cable systems is inherently tied to the performance of their solid insulation under combined electrical, thermal, and environmental stresses. Unlike liquid or gaseous dielectrics, which can partially restore dielectric strength after breakdown, solid insulation is non-self-restoring, meaning that degradation is cumulative and irreversible once initiated (Alqtish et al., 2025). This underscores the necessity of understanding and accurately classifying insulation failure modes to inform preventive maintenance and asset management strategies.

Intrinsic and Streamer Breakdown Mechanisms

Intrinsic breakdown occurs when the applied electric field exceeds the inherent dielectric strength of the insulation material, typically on the order of 10^6 *V/cm* within nanoseconds, assuming an absence of voids, impurities, or mechanical defects. This breakdown is dictated by the molecular and electronic structure of the material (Montanari et al., 2024).

Streamer breakdown, conversely, is initiated by partial discharges (PD) within voids or gaseous inclusions in or adjacent to the dielectric. Electrons, accelerated by the local field, gain enough energy between collisions to ionize surrounding molecules, initiating an avalanche process. This mechanism is particularly relevant in polymeric insulations such as PVC and PE when voids or microcavities are present (Wang et al., 2025). The voltage stress across a void can be estimated as:

$$V_1 = \varepsilon_r \cdot \frac{t}{d} \cdot V_a \quad \text{...(2)}$$

where:
V_1 = voltage across the void (V)
εr = relative permittivity of the insulation
t = void thickness (m)
d = total insulation thickness (m)
V_a = applied voltage (V)

If V_1 exceeds the breakdown voltage of the void's medium, PD activity will initiate, potentially leading to insulation erosion and failure.

Thermal Aging and Moisture-Accelerated Degradation

Thermal breakdown arises when heat generation surpasses dissipation, creating a feedback loop that accelerates degradation. The temperature rise is given by:

$$\Delta T = R_t \cdot q \tag{3}$$

where:
ΔT = temperature rise (°C)
R_t = thermal resistance (°C/W)
q = heat flow (W)

In LV distribution systems, overload currents and I^2R losses in conductors drive conductor temperatures beyond design limits, transferring thermal stress to insulation. Moisture ingress exacerbates this process, altering polymer decomposition pathways and degrading mechanical and dielectric properties. For example, Wu et al. (2025) demonstrated that PE sheaths exposed to high humidity exhibited significantly different thermal decomposition characteristics compared to dry conditions, with increased volatile release and accelerated oxidation (Wu et al., 2025). Similarly, Xu et al. (2025) found that damp heat aging in PVC not only reduced dielectric strength but also altered its flame retardancy profile (Xu et al., 2025).

Conductor Losses and Heat Transfer Constraints

$$P = I^2 \cdot R \tag{4}$$

where:
P = power loss (W)
I = current (A)
R = AC resistance (Ω)

In AC systems, resistance is increased by skin effect and proximity effect, which reduce the effective cross-sectional area available for current flow. In high-load scenarios, this leads to uneven heating and thermal hotspots. The ability of the cable system to dissipate heat can be characterized by thermal conductivity:

$$k = \frac{q}{A \cdot (\Delta T / l)} \tag{5}$$

Where:
k = thermal conductivity (W/m°C)
A = conductor cross-section (m²)
l = length (m)

In buried cables, soil composition and compaction significantly influence R_t and thus ΔT. Acidic soils, as highlighted by Liang et al. (2024), can further reduce insulation resistance through chemical attack, accelerating failure (Liang et al., 2024).

Dielectric Losses and Diagnostic Indicators

$$I_c = \omega \cdot C \cdot V \tag{6}$$

Where:
I_c = capacitive current (A)

ω = angular frequency (rad/s)
C = capacitance (F)
V = voltage (V)

However, real insulation systems exhibit a loss angle (δ), representing the phase displacement between voltage and current due to dielectric losses. Montanari et al. (2024) emphasize that tracking $\tan \delta$ over time is an effective method for non-destructive insulation health assessment, enabling predictive maintenance decisions (Montanari et al., 2024).

Integrated Implications for Condition-Based Maintenance

The interplay between electrical breakdown mechanisms, thermal stress, moisture ingress, and environmental contamination creates a multifactorial degradation pathway. Implementing a condition-based maintenance framework that integrates PD localization (Alqtish et al., 2025), impedance phase angle analysis (Wang et al., 2025), and thermal profiling can extend service life and reduce unplanned outages. Moreover, understanding environmental effects, such as damp heat aging (Xu et al., 2025) and soil chemistry (Liang et al., 2024), allows for targeted interventions in cable design, installation, and monitoring strategies.

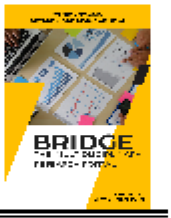
CONCLUSION

This study confirms that low-voltage cable insulation degradation in distribution networks is governed by a complex interaction of thermal, electrical, and environmental stress factors. Field measurements demonstrated that sustained overloading and phase imbalance significantly elevate conductor temperatures, intensifying thermal stress and accelerating insulation aging. The degradation process was primarily driven by intrinsic electrical breakdown, streamer-induced partial discharge activity, dielectric losses, and limitations in heat dissipation, which collectively reduce dielectric strength and compromise the mechanical integrity of polymeric insulation materials.

The results further indicate that environmental conditions, particularly high humidity and acidic soil, play a critical role in accelerating chemical and physical deterioration. These external factors exacerbate moisture ingress, promote partial discharge initiation, and intensify thermal aging, thereby shortening the effective service life of low-voltage cable systems. The combined influence of operational and environmental stress highlights the inadequacy of time-based maintenance approaches for managing insulation health.

From a practical perspective, the findings underscore the importance of implementing condition-based monitoring strategies that integrate dielectric spectroscopy, partial discharge diagnostics, impedance phase angle analysis, and thermal assessment. Such approaches enable early fault detection, support predictive maintenance planning, and enhance asset management efficiency in low-voltage distribution networks.

Future research should focus on long-term monitoring and statistical life modeling to quantify degradation progression under varying operational and environmental conditions. Expanding this framework to different insulation materials and installation environments would further strengthen



its applicability and contribute to the development of more resilient and sustainable power distribution systems.

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