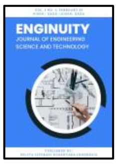

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Thermal and Environmental Degradation Mechanisms of Low-Voltage Cable Insulation: Diagnosis and Predictive Maintenance Strategies

Dekki Sandi Nugraha[1*], Dwi Agus Riyanto[2]
[1,2] Electrical Engineering, Sekolah Tinggi Teknologi Nusantara Lampung, Lampung, Indonesia
* Corresponding author: *dekkisandi@sttnlampung.ac.id*

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ABSTRACT

This study investigates the multifactorial degradation mechanisms of low-voltage cable insulation in distribution networks, focusing on the PR009 transformer substation as a representative case. Field measurements revealed frequent overloading and unbalanced phase currents, leading to elevated conductor temperatures and intensified thermal stress on polymeric insulation. The analysis identified intrinsic breakdown, streamer-induced partial discharges, thermal overload, moisture ingress, and environmental contamination particularly acidic soil as key contributors to accelerated insulation aging. Resistive heating *(I^2R losses)*, dielectric losses, and limited thermal conductivity were found to synergistically reduce dielectric strength and alter the mechanical stability of insulation materials. Laboratory modeling and theoretical calculations confirmed the role of local field enhancement in voids, moisture-driven chemical degradation, and cumulative erosion from partial discharge activity. The findings emphasize the need for advanced condition-based monitoring using dielectric spectroscopy, partial discharge localization, and impedance phase angle analysis to enable early fault detection. Preventive strategies, including load balancing, thermal management, improved joint maintenance, and the use of moisture-resistant, thermally stable insulation materials, are recommended to extend service life, minimize unplanned outages, and optimize asset management in low-voltage distribution systems. This research contributes to the understanding of insulation failure pathways and provides practical guidance for utilities to implement predictive maintenance frameworks tailored to environmental and operational stress factors.

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 [1].

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 [2]. 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 [3]. 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 [4].

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 [5]. 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 [6].

RESEARCH METHOD

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 [4], [7]. 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 [3].

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.

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

Where $\boldsymbol{R_i}$ 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 $\boldsymbol{R_i}$ 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 [8].

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 [9]. 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.

RESULT 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 [10]. 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 [11].

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 [12].
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:

$$\Delta T = R_t \cdot q \quad \text{(3)}$$

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 [13]. Similarly, Xu et al. (2025) found that damp heat aging in PVC not only reduced dielectric strength but also altered its flame retardancy profile [14].

Conductor Losses and Heat Transfer Constraints

Conductor heating due to resistive losses is described by:

$$P = I^2 \cdot R \quad \text{....................................(4)}$$

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:

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

Where:
k = thermal conductivity (W/m°C)
A = conductor cross-section (m^2)
l = length (m)

In buried cables, soil composition and compaction significantly influence $\mathbf{R}_t$ and thus ΔT. Acidic soils, as highlighted by Liang et al. (2024), can further reduce insulation resistance through chemical attack, accelerating failure [15].

Dielectric Losses and Diagnostic Indicators

In an ideal capacitor, capacitive current is given by:

$$I_c = \omega \cdot C \cdot V \quad \text{..................................(6)}$$

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 [11].

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 [10], impedance phase angle analysis [12], and thermal profiling can extend service life and reduce unplanned outages. Moreover, understanding environmental effects, such as damp heat aging [14] and soil chemistry [15], allows for targeted interventions in cable design, installation, and monitoring strategies.

CONCLUSION

This study demonstrates that the degradation of low-voltage cable insulation in the distribution network is the result of a multifactorial process involving intrinsic electrical breakdown, streamer-induced partial discharge, thermal overloading, moisture ingress, and environmental contamination. Field measurements at the PR009 transformer substation revealed that operating currents frequently approached or exceeded the cable's ampacity, leading to elevated conductor temperatures and increased thermal stress on the insulation.

Experimental analysis and theoretical modeling confirmed that resistive heating (I^2R losses), dielectric losses, and thermal conductivity limitations are primary contributors to insulation aging. Moreover, environmental factors such as high humidity and acidic soil conditions were found to accelerate chemical and physical degradation mechanisms, altering the dielectric response and mechanical properties of polymeric insulation materials.

The findings underscore the importance of integrating advanced condition-monitoring techniques such as dielectric spectroscopy, partial discharge localization, and impedance phase angle analysis into predictive maintenance programs. Such integration can significantly extend service life, reduce unplanned outages, and optimize asset management strategies for low-voltage distribution systems.

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