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Advanced Evaluation of Oil-Filled Transmission Cable Terminations: Failure Assessment & Reliability Enhancement

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Abstract: ***Oil-filled transmission cable terminations are among the most critical and failure-prone components of HV and EHV transmission cable systems because of their complex electrical stress-control and sealing interfaces. A key challenge is detecting latent degradation mechanisms that develop internally and thus escape periodic inspections. Although previous studies have examined individual failure mechanisms, few have integrated forensic investigation, material characterisation, field assessment, and reliability evaluation of ageing oil-filled transmission cable terminations. This paper delivers a comprehensive assessment of 132 kV and 380 kV oil-filled cable terminations operating in the Saudi transmission network. The investigation combined forensic dissection, X-ray imaging, and field inspections to identify the dominant degradation mechanisms. The results highlight two primary reliability concerns: silicone stress-cone degradation and sealing-system deficiencies that led to oil leakage, moisture ingress, and corrosion. The study shows that advanced diagnostics can detect hidden defects and proposes a reliability-centred framework for condition assessment, monitoring, and asset management. The findings provide practical guidance to improve transmission system reliability, reduce outage risk, and extend asset service life.***

Keywords*: *Oil-filled Transmission Cable Terminations, Stress Cone, Oil leakage, AGEING, Forensics, Root Cause Analysis.

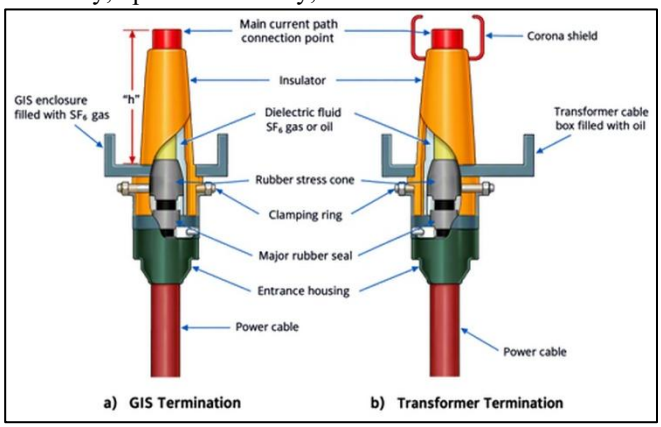
Nomenclature:
HV: High Voltage
EHV: Extra High Voltage
GIS: Gas Insulated Switchgear
kV: kilo Volt
XLPE: Cross-linked polyethene
PD: Partial Discharge
DGA: Dissolved Gas Analysis
OM: Optical Microscopy
SEM: Scanning Electron Microscopy
EDS: Energy Dispersive Spectroscopy
FTIR: Fourier Transform Infrared Spectroscopy
DSC: Differential Scanning Calorimetry
RTV: Room Temperature Vulcanization
LSR: Liquid Silicone Rubber
EPDM: Ethylene Propylene Diene Monomer

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I. INTRODUCTION

Highly reliable underground transmission systems are essential to modern power networks. Within these systems, cable terminations serve as the interface between high-voltage cables and equipment such as transformers and gas-insulated switchgear (GIS), as shown in Fig. 1. Although transmission cables are generally highly reliable, cable terminations have historically been regarded as one of the weakest elements in the overall circuit because of their complex electrical, mechanical, and sealing interfaces. The performance of these accessories directly influences network reliability, operational safety, and maintenance costs.

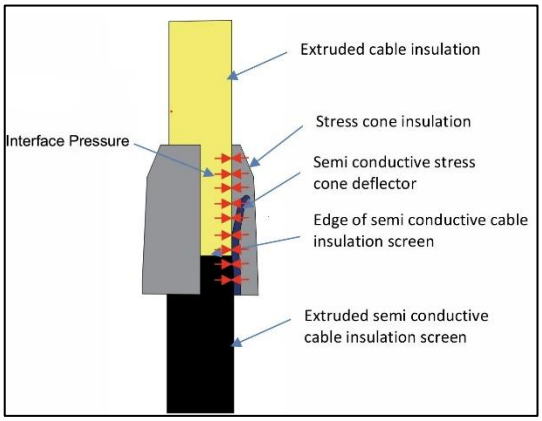


[Fig.1: Typical Oil-Filled Transmission Cable Terminations (a) GIS Termination (b)Transformer Termination]

The continued expansion of the transmission grid has led to the widespread deployment of oil-filled cable terminations in High Voltage (HV) and Extra High Voltage (EHV) systems. Many of these installations operate under harsh environmental conditions, including elevated ambient temperatures, service cycling, and extended service life. These factors can accelerate degradation and increase susceptibility to hidden internal failures.

The stress cone is a critical component of oil-filled transmission cable terminations, designed to control electric-field distribution at the cable insulation-screen discontinuity. Degradation of the stress-cone material or loss of interface pressure can create localized electrical stress concentrations that may initiate partial discharge and long-term insulation deterioration. Fig.2 illustrates a typical rubber stress cone in oil-filled transmission cable terminations.

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[Fig.2: Rubber Stress Cone for Cable Terminations]

This paper highlights recurring issues, including stress cone deterioration, oil leakage, moisture ingress, and limited condition-monitoring capabilities. These failures can lead to prolonged outages, safety hazards, transformer damage, and higher lifecycle costs. To address these challenges, a detailed program combining laboratory forensics, field inspections, and material characterization was implemented to identify root causes and develop strategies to improve reliability.

II. LITERATURE REVIEW AND KNOWLEDGE GAP

Oil-filled transmission cable terminations remain an important component of HV and EHV transmission networks. The latest IEC 62271-209 (2022) establishes requirements for Oil (fluid)-filled and dry-type cable terminations connected to gas-insulated switchgear [1], while IEC 60840 (2020) and IEC 62067 (2022) specify test methods and performance requirements for cable systems and accessories for rated voltages above 30 kV up to 150 kV [2] and above 150 kV up to 500 kV [3], respectively. These standards emphasize partial discharge testing, protection against water ingress [2] [3], and pressure and leak-rate testing of cable termination systems to support reliable long-term operation [1].

Localized electric-field enhancement in the aged stress-cone region can accelerate degradation of semiconducting materials and promote incipient faults in oil-filled transmission cable terminations (sealing ends). The associated partial discharge activity may remain intermittent and difficult to detect during routine condition assessment, potentially delaying fault identification until substantial deterioration has occurred [4].

Cable terminations control electrical stress in shielded power cables. However, they are prone to partial discharges (PD) caused by increased voltage stress, moisture ingress, and poor workmanship during installation, so online PD detection is necessary to assess their condition [5].

Moisture ingress is a significant degradation mechanism in oil-filled cable terminations, reducing interfacial dielectric strength, distorting the electric field, and increasing the risk of partial discharge and insulation breakdown [6].

Thermomechanical ageing degrades the mechanical properties of silicone rubber and XLPE in oil-filled cable terminations, decreases interfacial pressure, increases microcavity formation, and weakens electrical breakdown strength [7].

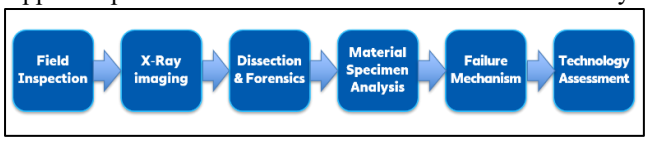
Although previous studies have investigated oil-filled cable terminations for partial discharge phenomena and diagnostic techniques [4][5], oil-filled cable termination failure mechanisms associated with moisture ingress, workmanship, and electrical stress concentration [6], and insulation ageing in silicone rubber material [7], limited research has integrated forensic dissection, advanced material characterization, field assessment, and reliability analysis specifically for ageing oil-filled cable terminations. This study addresses this gap by combining laboratory evidence and field observations to identify latent failure mechanisms and establish reliability-centred asset management recommendations for HV/EHV oil-filled terminations.

III. METHODOLOGY

A. Investigation Framework

A comprehensive investigation framework shown in Fig. 3 was developed to evaluate oil-filled transmission cable terminations from multiple perspectives. The study integrated forensic laboratory assessments, material characterization, field inspections, and reliability evaluation to establish a complete understanding of degradation mechanisms and service-performance concerns.

The investigation correlated physical evidence from dismantled components with observations from operating installations. This integrated approach validated laboratory findings against actual utility operating conditions and supported practical recommendations to enhance reliability.



[Fig.3: Methodology and Evaluation Framework]

B. Laboratory Evaluation

Two removed transmission cable terminations underwent complete forensic disassembly and examination:

- 132 kV oil-filled cable termination.
- 380 kV oil-filled cable termination.

C. Laboratory Investigations Included

- X-ray imaging.
- Visual inspections.
- Dimensional measurements.
- Oil sampling.
- Component dissection.
- Failure mechanism assessment.

Attention focused on sealing systems, stress cone components, insulation interfaces, metallic hardware, and signs of electrical activity or moisture ingress.

D. Material Characterization

Representative material samples extracted during disassembly were analyzed using:

- Optical Microscopy (OM).
- Scanning Electron Microscopy (SEM).
- Energy Dispersive Spectroscopy (EDS).
- Fourier Transform Infrared Spectroscopy (FTIS).
- Differential Scanning Calorimetry (DSC).

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These techniques were applied to assess material composition, contamination, ageing behaviour, thermal properties, and degradation characteristics.

E. Field Assessment

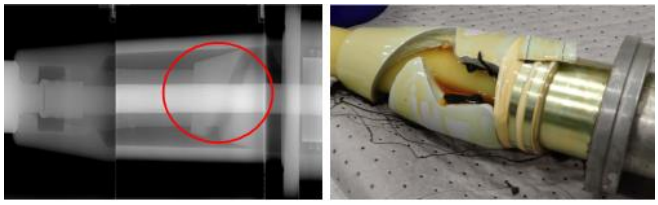
Field inspections were conducted on more than forty transmission cable terminations installed at substations and generating stations. The surveyed population included transformers, GIS, and outdoor terminations operating at 132kV and 380kV. The inspections focused on identifying:

- Oil leakage.
- Installation deficiencies.
- Monitoring capability limitations.
- Signs of insulation degradation.
- Historical failure patterns.

IV. RESULT AND DISCUSSION

A. 132 kV Oil-Filled Cable Termination Lab Evaluation

A notable finding was a split silicone stress cone after approximately 24 years of service. Fig. 4 shows X-ray scans revealing a spiral crack through the stress-cone body, which was visually observed upon dissection. No evidence of tracking, erosion, or partial discharge was observed on adjacent insulation surfaces, suggesting the split likely developed late in service life and increased after removal.



(a) (b)

[Fig.4: Split in Stress Cone: (a) Revealed by X-ray and (b)Visually Observed During Inspection]

Material analysis revealed:

- No significant polymer degradation.
- No moisture ingress.
- No evidence of thermal damage.
- Good condition of sealing components.

The root cause was likely long-term ageing of the Room Temperature Vulcanisation (RTV) silicone in the stress cone.

B. 380 kV Cable Oil-Filled Termination Lab Evaluation

The 380 kV Cable Oil-Filled Termination sample was removed after only 22 months of service. We dissected and inspected it at each step. Fig. 5 shows the oil leakage paths observed in the Lead wipe of the cable oil-filled termination.



(a) (b)

[Fig.5: Lead Wipe's Oil Leakage Paths: (a) Lead Wipe Crack and (b) Lead Wipe Pinhole]

Key findings from the inspection included:

- Pinhole defects in lead wipe.
- Cracks in lead wipe.
- Oil leakage along cable screens.
- Copper corrosion (patina formation).
- Moisture ingress in cable layers.

Failure mechanisms were primarily associated with workmanship-related oil leakage rather than material degradation or manufacturing defects.

Material Sample Analysis included 10 samples collected from the two dissected oil-filled cable terminations, which were tested using characterization techniques to assess material integrity, thermal behaviour, and degradation. Material testing confirmed:

- No systemic material defects.
- No stress cone degradation.
- Moisture-related corrosion products.
- Oil contamination outside intended sealing boundaries.

Evidence strongly indicated that workmanship-related sealing deficiencies were combined with thermal and mechanical stress.

C. Field Inspection Findings

The team inspected more than forty terminations across Saudi Arabia. The evaluation covered transformers, GIS, and outdoor terminations at 132 kV and 380 kV.

Field inspections confirmed that oil leakage remains one of the most common reliability concerns for oil-filled transmission cable terminations. Leakage was observed in expansion tanks, flexible hoses, and sealing systems.

Historical records also indicated pressure loss and partial discharge activity at several installations. Key observations included:

- Oil leakage from expansion tanks and flexible hoses.
- Historical partial discharge activity.
- Limited pressure and oil-level monitoring.
- No significant issues observed on dry-type installations.

Substations reported historical termination failures and oil leakage incidents, indicating fleet-wide reliability risks. The risks identified during the field assessment are given in Table I.

Table I: Reliability Risk Areas Identified

Sr.	Observation	Risk Area
1.	Split RTV stress cones	Stress Cone Ageing
2.	Expansion tanks, hoses, lead wipes	Oil Leakage
3.	Corrosion of copper shielding	Moisture Ingress
4.	Limited diagnostic visibility	Monitoring
5.	Inconsistent condition assessment	Maintenance

V. DISCUSSION

The investigation highlighted three dominant reliability threats:

A. Stress Cone Ageing

Stress cone splitting suggests ageing-related degradation mechanisms in RTV silicone materials. Although forensic analysis detected no electrical activity, loss of elasticity and interface pressure represent a latent reliability concern that can eventually compromise dielectric performance.

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The findings suggest that ageing RTV silicone stress cones pose a fleet-wide reliability issue, not isolated defects in individual installations.

B. Oil Leakage

Oil-filled terminations remain vulnerable to leakage through seals, pressure systems, and lead wipes. Internal leaks may go undetected until they compromise dielectric integrity.

Internal leakage paths that routine visual inspections cannot detect are especially concerning. These hidden degradation mechanisms can progress undetected until significant deterioration has already occurred.

C. Limited Monitoring

Many installations lack oil-level / pressure monitoring and remote alarm notifications. As a result, degradation can progress unnoticed until catastrophic failure occurs.

D. Diagnostic Effectiveness

The results demonstrate the value of advanced diagnostic technologies in identifying hidden deterioration mechanisms. The investigation showed that:

- X-ray imaging successfully identified hidden structural defects.
- Material characterization provided valuable insights into degradation mechanisms.
- Condition-based diagnostic approaches significantly improve assessment capability.
- Multiple diagnostic methods used together maximize defect detectability.

E. Dry-Type Termination Technologies

Dry-type terminations eliminate many risks associated with oil terminations, significantly reducing fire hazards and maintenance requirements. However, dry types are available in limited sizes and offer less flexibility in alignment precision and field movement.

VI. RECOMMENDATIONS

Based on laboratory and field findings, the following actions are recommended:

A. Specification Improvements

Utility technical specifications should be updated to:

- Incorporate an oil-pressure and/or oil level monitoring system with alarms.
- Improve cable termination oil sealing requirements.
- Strengthen factory quality assurance criteria.
- Specify more recent stress cone materials such as Liquid Silicone Rubber (LSR) or Ethylene Propylene Diene Monomer (EPDM) in place of RTV silicone

B. Diagnostic Enhancement

Utilities should expand the use of:

- Partial discharge (PD) monitoring.
- Dissolved gas analysis (DGA)
- X-ray inspections of ageing assets.
- Infrared thermographic surveys.
- Condition-based asset assessment programs.

C. Asset Management Strategy

A formal risk-based asset management framework should be established to:

- Identify at-risk termination populations.
- Prioritise ageing RTV stress cone designs.
- Develop phased replacement programs.

Table II lists the reliability gaps identified in the investigations and the recommended improvements.

Table II: Reliability Gaps and Recommended Improvements

Sr.	Observation	Risk Area
1.	Monitoring	Implement oil pressure/level monitoring
2.	Diagnostics	Expand PD, DGA, & X-ray inspections
3.	Materials	Replace ageing RTV stress cones
4.	Installation	Strengthen workmanship controls
5.	Asset Management	Risk-rank and prioritize critical assets

VII. CONCLUSION

A comprehensive evaluation of 132 kV and 380 kV oil-filled cable terminations identified stress cone ageing, oil leakage, moisture ingress, and monitoring limitations as the primary contributors to reliability risk.

Laboratory investigations showed that RTV silicone stress cones can deteriorate over time without obvious electrical symptoms, creating latent failure conditions in ageing installations. The evaluation further confirmed that sealing-system deficiencies can cause oil leakage and moisture ingress even when insulation materials remain largely unaffected.

Combining forensic dissection, material characterization, field inspections, and advanced diagnostics provided valuable insight into the degradation mechanisms affecting transmission cable accessories. The recommendations provide a practical pathway to improve reliability, reduce failure risk, enhance operational resilience, and support lifecycle management of oil-filled cable termination fleets.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Ethical Approval and Consent to Participate:** The data provided in this article are exempt from ethical approval or participant consent requirements.
- **Data Access Statement and Material Availability:** Access Statement: The data supporting the findings of this study are included within the article and in the associated laboratory records. Additional technical details may be available from

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the corresponding author upon reasonable request and subject to applicable organizational requirements.

- **Author's Contribution:** Murad Anwer Muhammad Anwer contributed to conceptualization, laboratory investigation, data analysis, interpretation of results, and manuscript preparation, and served as the corresponding author. Ahmed A. Albahli contributed to field investigations, data collection, failure analysis, engineering validation, interpretation of results, development of engineering recommendations, and manuscript review. Tiebin (Tom) Zhao contributed subject-matter expertise in underground transmission cable systems, laboratory investigation, data analysis, interpretation of results, and critical review of the manuscript. All authors reviewed and approved the final manuscript.

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