Strategies for Mitigating Degradation of Medium Voltage Electrical Equipment in Harsh Saline Environments

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Strategies for Mitigating Degradation of Medium Voltage Electrical Equipment in Harsh Saline Environments

Benemmane Elhassan†, *Associate Member, IET*, Benemmane Omar†, *Member, IEEE*

***Abstract*—This paper presents a comprehensive analysis of the degradation mechanisms affecting medium voltage (MV) electrical equipment in the harsh saline and windy environment of the Laayoune region of Morocco. Corrosion of metal structures and accessories, as well as deterioration of composite insulators, are the two major failure modes identified. A systematic approach involving data analysis, field inspections, and laboratory testing was employed to understand the underlying physical and chemical processes. Based on these insights, several protection strategies are proposed and techno-economically evaluated, including RTV silicone coatings, upgraded materials, design modifications, and maintenance practices. A roadmap for short, medium, and long-term implementation of the optimal solutions is laid out. The findings provide valuable guidance for utilities facing similar challenges in corrosive environments globally.**

***Index Terms*—Coastal environments, composite insulators, corrosion protection, equipment degradation, medium voltage equipment, power distribution reliability, RTV coatings, saline atmosphere.**

I. INTRODUCTION

THE Electrical utilities face major challenges in ensuring reliable operation of transmission and distribution systems in coastal and offshore environments. The combination of airborne salinity, moisture, temperature variations, and sand/dust causes accelerated aging and premature failure of various grid assets [1], [2]. This inevitably leads to increased maintenance costs and reduced power availability and quality for consumers.

Utilities therefore have a strong interest in developing cost-effective strategies for prevention, mitigation or accommodation of the different degradation processes through appropriate selection of materials, coatings, designs and maintenance practices [3]. At the same time, these strategies must take into account the site-specific environmental parameters as well as the realistic constraints of large power networks in terms of performance requirements, life-cycle costs, and ease of implementation and upkeep.

This paper presents a case study of the medium voltage (MV) infrastructure operated by the Laayoune Regional Directorate of the National Office of Electricity and Drinking Water (ONEE) in south-western Morocco. This coastal desert area is subjected to a unique combination of stresses - high salinity blowing inland from the Atlantic Ocean, wide temperature swings between day and night, low rainfall, high winds transporting sand and dust particles.

As a result, ONEE has experienced significant reliability and maintenance issues, mainly related to corrosion of towers/poles, line hardware and accessories, as well as failure of glass and composite insulators. A comprehensive applied research project was undertaken to characterize the local environment, understand the degradation phenomena, and identify optimized solutions that can be deployed at scale.

II. CONTEXT AND PROBLEM ANALYSIS

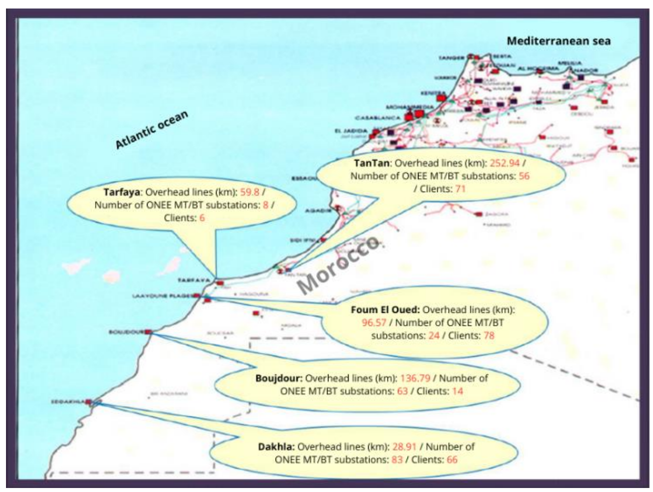

Fig. 1. Map of MV network exposed to coastal environment in Laayoune region.

A. Network Description

The Laayoune Regional Directorate manages an extensive territory characterized by a long Atlantic coastline interspersed with desert landscape. The MV network consists of overhead lines and substations operating at 22 kV and 60 kV. A significant portion of this infrastructure is exposed to the aggressive maritime conditions, notably in the cities of Tan-Tan, Tarfaya, Laayoune, Boujdour and Dakhla.

Figure 1 shows a map of the region with the affected MV

This paragraph of the first footnote will contain the date on which you submitted your paper for review, which is populated by IEEE. Elhassan and Omar contributed equally to this work as co-first authors.

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Part of the experimental work was conducted at ONEE's Research Center in Casablanca, Morocco.

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corridors highlighted. Based on geographical information system (GIS) analysis, it is estimated that 30-50% of the total MV line length is located within 3-5 km from the ocean, depending on the province. The assets at risk include concrete poles, lattice steel towers, conductors, insulators, line hardware and switchgear.

Fig. 2. Exposure of Electrical Assets to Harsh Conditions.

Figure 2 illustrates the various environmental stresses affecting MV equipment in the coastal region, including saline spray from the ocean, industrial pollution, and harsh weather conditions.

B. Failure Statistics and Trends

Reliability data over the period 2020-2023 was compiled and analyzed to identify the main outage causes and trends. Table I breaks down the incidents by equipment category, revealing that degradation of conductors, clamps, insulators and MV/LV substation components account for the bulk of environment-related failures.

TABLE I
BREAKDOWN OF INCIDENTS DUE TO NATURAL CAUSES BY EQUIPMENT CATEGORY

2020		2021	
Damage Category	Percentage	Damage Category	Percentage
Conductor	45%	Conductor	33%
Distribution Branches	28%	Distribution Branches	28%
ONEE's MV/LV Substations	11%	End Boxes	11%
End Boxes	10%	ONEE's MV/LV Substations	9%
Poles	2%	Insulator	7%
Client's MV/LV Substations	2%	Poles	6%
Switchgear	2%	Surge Arrester	3%
Insulator	0%	Switchgear	2%
Surge Arrester	0%	Client's MV/LV Substations	1%
2022		**2023**	
Damage Category	Percentage	Damage Category	Percentage
Conductor	39%	Conductor	44%
Distribution Branches	33%	Distribution Branches	26%
Insulator	8%	Insulator	11%
Client's MV/LV Substations	7%	Client's MV/LV Substations	7%
ONEE's MV/LV Substations	5%	Poles	5%
Poles	4%	ONEE's MV/LV Substations	4%
Switchgear	4%	End Boxes	3%
Surge Arrester	0%	Surge Arrester	0%
End Boxes	0%	Switchgear	0%

Moreover, the coastal provinces exhibit a higher incident rate compared to inland areas, as illustrated in Table II. While a global decrease can be noted as a result of past corrective actions by ONEE, the failure rate remains unacceptably high for the marine sites.

TABLE II
EVOLUTION OF ENVIRONMENT-RELATED INCIDENTS IN COASTAL AREAS

Coastal City	Incidents (2020)	Incidents (2021)	Incidents (2022)	Incidents (2023)
Boujdour	11	3	6	5
Dakhla	9	9	18	5
Foum El Oued	13	12	17	10
TanTan	26	13	11	9
Tarfaya	2	1	1	2
Total	**61**	**38**	**53**	**31**

The outage events were further classified based on the underlying failure mechanisms, aided by inspections of selected line segments. Two prevalent issues were diagnosed:

1) **Corrosion of galvanized steel towers, poles and hardware**
The constant exposure to salt spray leads to accelerated loss of the protective zinc layer and rusting of the underlying steel substrate. This weakens the mechanical strength and, in some cases, has led to collapsed poles and towers. Corrosion also affects grillages, crossarms, brackets, bolt assemblies and conductor accessories like clamps, compression fittings, vibration dampers, etc. Formation of rust layers with poor conductivity contributes to local overheating and failure.
2) **Degradation of ceramic and composite insulators**
The combination of airborne pollution accumulating on the insulator surface and wetting by morning dew/fog gives rise to development of conductive films, causing increased leakage current, dry band arcing and flashovers. In the case of glass/porcelain insulators, the thermal shocks during the daily temperature cycling lead to cracking shells. For composite (polymeric) insulators, erosion of the housing and shedding damage due to arcing is observed, sometimes exposing the internal fiberglass rod.

These findings served to guide the focus of the experimental work described in the next section to better elucidate the governing physical/chemical processes and test the performance of alternative materials and methods.

III. EXPERIMENTAL ANALYSIS OF DEGRADATION MECHANISMS

A. Approach and Methodology

The technical study involved three main activities:

1) **Sampling and testing of components removed from service**
Specimens of severely damaged insulators, tower/pole steel coupons, and conductor hardware were collected during the field inspections. These were subjected to a battery of measurements and laboratory analyses at ONEE's Research Center in Casablanca to characterize their surface condition, corrosion products, morphology and microstructure. Standardized tests like ESDD (equivalent salt deposit density) [4], NSDD (non-soluble deposit density) [5], SEM/EDX, and metallography were performed.

2) **Comparative tests of new and aged insulator designs**
In parallel, a test protocol was designed to compare the performance of different commercially available MV insulator options under representative stress conditions. Full-scale insulator strings as well as material samples (silicone rubber) were exposed on a test rack installed near the coastline at Laayoune. The set up allowed simultaneous monitoring of leakage current, flashover voltage, hydrophobicity class [6] and material aging parameters. This was complemented by laboratory aging tests like salt fog [7] and accelerated weathering.

3) **Evaluation of coatings and accessories**
Lastly, the corrosion protection efficacy of a range of coatings and hardware accessories was evaluated, first through laboratory screening and then field trials. The coating tests focused on room-temperature vulcanizing (RTV) silicone rubbers, applied both on porcelain/glass insulators and steel structures. The hardware accessories included corrosion-resistant alloys for conductor fittings as well as covers, seals and greases.

B. Results and Discussion

1) **Characterization of In-Service Components**
The various analysis techniques provided new insights into the prevailing degradation mechanisms in the coastal environment:

a) Loss of galvanization and steel corrosion:
Measurements of the zinc coating thickness according to ISO 1461 [8] showed that for some tower parts removed from service, more than 80% of the original galvanizing was lost. Figure 2, from site inspections at FOUM EL OUED, shows severe uniform corrosion on tower components located 100m-10km from the coast, revealing near-complete degradation of the protective zinc coating and underlying steel structure. NSDD values exceeding 1 mg/cm2 were recorded, confirming the high concentration of insoluble matter (sand, dust, salts) accumulating on the hardware surfaces.

Fig. 3. Photographic evidence of galvanization loss on tower structures at FOUM EL OUED.

The corrosion products were identified by XRD to be primarily goethite α-FeOOH and lepidocrocite γ-FeOOH. This is consistent with the frequent wet/dry cycling and airborne chloride chemistry promoting these oxyhydroxide phases [9].

b) Insulator surface degradation:
ESDD measurements on glass/porcelain insulators were in the range 0.1-0.3 mg/cm2, which exceeds the typical values used in IEC 60815-1 [10] to define "very heavy" pollution severity. However, for composite insulators, the ESDD was generally lower due to the initial hydrophobicity of the silicone rubber surface.
Surface analysis using scanning electron microscopy (SEM) revealed significant differences between new and degraded insulators, as shown in Fig. 4. The new insulator surface (Fig. 4 (a)) exhibits uniform hydrophobic properties with well-distributed silicone fluid droplets, while the degraded surface (Fig. 4 (b)) shows severe deterioration and loss of hydrophobic properties. These microscopic changes lead to increased wetting and pollution accumulation. These effects are attributed respectively to the thermal stress fatigue caused by the heating/cooling cycles under pollution flashovers [11], and to partial discharges and arcing activity.

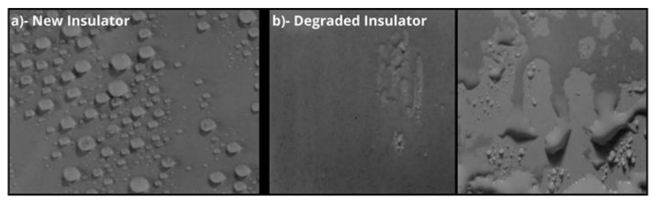

Fig. 4. SEM Analysis (New Insulator vs Degraded Insulator).

2) **Performance of Alternative Insulator Designs**
To address the challenges posed by harsh environments, it is essential to examine the weaknesses of conventional designs and evaluate alternative solutions. Fig. 5. illustrates the flashover mechanism in conventional insulators, where severe environmental conditions accelerate insulation breakdown. This process involves corona discharge, which occurs at sharp edges or points of insulators where high electric fields ionize the surrounding air, creating pathways for flashovers. This is compounded by dry band arcing, where localized heating due to evaporating moisture accelerates insulation failure. These vulnerabilities highlight the need for alternative solutions.

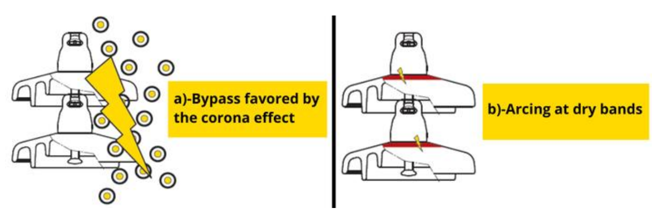

Fig. 5. Flashover Mechanism in Conventional Insulators.

To mitigate the mechanisms outlined in Fig. 5., RTV silicone coatings offer a proven solution by leveraging advanced material properties to maintain surface integrity and electrical performance. The protection mechanism of RTV silicone coatings is depicted in Fig. 6., showcasing their superior performance in mitigating such issues. The coatings leverage Low Molecular Weight Silicones (LMWS) to interact with surface contaminants, maintaining a high contact angle β that ensures hydrophobicity. This high contact angle (β) represents the hydrophobicity of the coated surface, ensuring water repulsion and preventing conductive pathways. The distinct angle (α) of water droplets reflects the coating's ability to isolate moisture from contaminants. These properties eliminate the risk of leakage currents, even in highly polluted conditions.

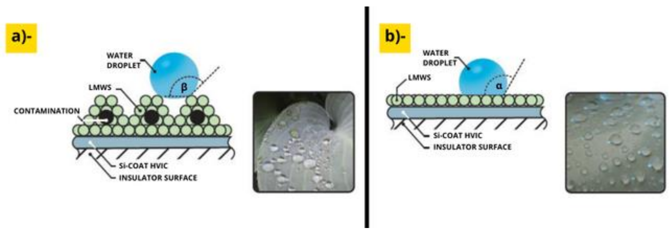

Fig. 6. Hydrophobicity Behavior of RTV Coatings.

Fig. 7. further contrasts the leakage current behavior on protected versus unprotected surfaces. RTV-coated insulators demonstrate a significant reduction in leakage current, as the hydrophobic barrier prevents conductive paths from forming. In contrast, unprotected surfaces exhibit active leakage currents, which can lead to power loss and increased maintenance requirements. These findings underscore the critical role of RTV silicone coatings in enhancing insulator reliability and service life in challenging environments. This reduction in leakage current directly translates to lower maintenance costs and improved operational efficiency, making RTV coatings a valuable investment for long-term insulator reliability.

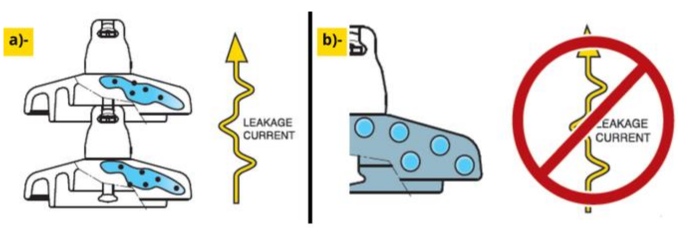

Fig. 7. Leakage Current Behavior Comparison.

In contrast, composite insulators performed significantly better, with leakage currents and order of magnitude lower. Among these samples, silicone rubber was found to outperform EPDM and cycloaliphatic materials in terms of hydrophobicity recovery [12]. However, none of the commercial designs managed to fully prevent erosion and tracking when exposed for more than 1 year in the extreme coastal site. This motivated the work on supplementary coatings and greases.

In summary, Conventional insulators are highly vulnerable to environmental stresses such as pollution and moisture, leading to mechanisms like corona discharge and dry band arcing that result in insulation breakdown. RTV silicone coatings, demonstrated in Fig. 6. and Fig. 7., mitigate these issues effectively by leveraging Low Molecular Weight Silicones (LMWS) to maintain hydrophobicity, reduce leakage currents, and enhance insulator reliability. Composite insulators, although superior to traditional designs, still require supplementary coatings for long-term performance in extreme conditions.

3) **Benefits of Coatings and Accessories**
The use of RTV silicone coatings on porcelain/glass insulators increased the flashover voltage by 20-30% in the salt-fog test. Similar results were demonstrated for steel tower parts. In both cases, service life is estimated by accelerated aging tests to exceed 10 years, provided appropriate surface preparation and coating thickness are implemented.
The most promising hardware accessory solutions consisted in:
   a) Using aluminum-alloy (EN 6082 or AS13) instead of galvanized steel for line clamp bodies.
   b) Selecting stainless steel nuts and bolts for corrosion-prone connections.
   c) Applying special sealing greases to prevent water infiltration in compression fittings.

These relatively simple measures can provide a cost-effective life extension to components that are compatible with the existing network practices.

IV. Recommendations and Roadmap

Based on the combination of failure analysis, experimental tests and initial field trials, the following recommendations are proposed for ONEE's MV networks in the Laayoune region:

A. Short-Term

1) Apply RTV silicone coatings to critical insulator sections and galvanized towers, prioritizing sites with abnormally high fault rates.
2) Replace heavily corroded hardware with aluminum alloy and stainless steel materials, and prepare a multi-year component replacement program.

B. Medium-Term

1) Retrofit existing porcelain/glass insulators in coastal regions with RTV silicone coatings as a palliative measure.
2) Adapt live-line maintenance practices to include periodic re-application of greases and cleaning of fittings.

C. Long-Term

1) Standardize the use of silicone rubber composite insulators with appropriate creepage distance (e.g., 50 mm/kV) and designs incorporating ATH filler for arcing resistance in new line construction and refurbishment.
2) Revise insulator selection and pollution mitigation philosophies for all new MV projects in coastal regions, integrating pollution severity assessments (e.g., ESDD, NSDD) into design specifications.

V. Conclusion

ONEE's application study has shed light on the complex degradation mechanisms affecting MV overhead assets in the corrosive environment of the Laayoune region. The main original contributions consist of the systematic diagnosis methodology applied, the comparative analysis of insulator solutions, and the practical guidelines for remedial measures combining engineering, work practices and specifications. While the coastal desert of south Morocco certainly presents some unique challenges, many of the lessons learned can be usefully applied by other power utilities facing accelerated aging of their infrastructure in marine/offshore conditions worldwide.

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