Comparative Assessment of Corona Behavior on Existing and Proposed 400-kV Composite Insulator Assemblies

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Abstract – *Composite long-rod insulators installed on the 400-kV overhead transmission lines at a site were found to exhibit corona discharge activity, indicated by dark surface spots and ultraviolet emissions concentrated near the energized end of the strings. Field inspections using visual, UV, and infrared scanning indicated localized corona activity on multiple circuits. To assess the issue, type tests—including corona extinction voltage, radio interference voltage (RIV), lightning impulse, and wet power frequency tests—were performed on new, cleaned, and in-service insulators. All samples complied with relevant utility standards, and electric-field simulations showed field intensities below corona-critical thresholds. Although laboratory and simulation results were satisfactory, field observations suggest the possibility that environmental pollution levels introduce conditions not fully replicated during testing, contributing to corona formation. A comparison of existing and proposed insulator assemblies revealed that current 400-kV installations generally lack grading rings, whereas the proposed configurations incorporate them, potentially improving electric-field distribution under polluted conditions. The investigation concludes that the observed black spots are directly associated with corona discharge and highlights the need to evaluate insulator design and hardware configuration for high-pollution environments.*

Keywords: *Composite Insulator, Corona Discharge, Electric-Field, RIV*

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I. Introduction

Composite long-rod insulators in high-pollution 400-kV networks have shown localized corona activity, including dark surface spots and localized discharge marks. These phenomena were consistently observed across multiple circuits in a coastal/desert environment as well as on comparable 400-kV installations constructed by other contractors. The affected insulator strings consist of composite units combined with V-jumper suspension and double-tension hardware assemblies.

Initial field observations indicated that the corona activity was concentrated near the energized end region of the insulator strings, particularly between the conductor attachment point and the mid-section of the long-rod units. The presence of dark spots suggested sustained partial discharge activity under energized conditions. Given the critical role of composite insulators in maintaining line reliability, a detailed investigation was initiated to assess the severity, root cause, and potential design or environmental factors contributing to the observed degradation.

This report presents the results of field inspections, ultraviolet corona imaging, infrared thermal scanning, type-test verification, electric-field simulations, and comparative hardware analysis. The objective is to determine whether the observed corona activity is attributable to insulator design, environmental pollution, hardware configuration, or a combination of these factors, and to evaluate the suitability of current insulator assemblies for long-term operation in high-pollution environments.

II. Field Diagnostics and Data Collection

Field inspections of energized lines revealed dark surface spots near the energized ends of the insulator strings. Field inspections revealed dark corona-induced spots near the energized end. Fig. 1 to 3 show photographs taken at the site. A total of six circuits and fourteen insulator assemblies were surveyed between January and March 2021. UV inspections were performed using an OFIL DayCor® camera (calibrated 2020), and IR measurements were taken using a Fluke Ti450 thermal imager. Ambient humidity ranged from 45–70%, temperatures from 24–33°C, and line loading was between 60–85% of rated current. UV counts ranged from

5–18 events/min near the energized end. No abnormal IR temperature rise was detected; therefore, thermal results are not used for comparative assessment.

The units clearly show signs of black spots near the energized end portion of the strings. These spots were observed on double-tension, suspension, and jumper strings. The same composite insulator type was used in all configurations.



Fig. 1. Site photograph of a double-tension composite insulator assembly



Fig. 2. Site image of an I-Jumper composite insulator assembly



Fig. 3. Close-up image of a composite insulator

A. Ultraviolet Imagery

Visual inspection, ultraviolet corona scanning & infrared thermal scanning of the affected (live) insulators were performed using specialized equipment to identify localized discharge. Figs. 4–7 show ultraviolet emissions near the energized ends of the insulators.



Fig. 4. Ultraviolet image of a V-Suspension string

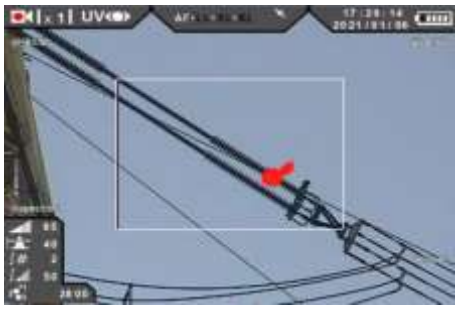


Fig. 5. Ultraviolet image-1 of a Double-Tension string

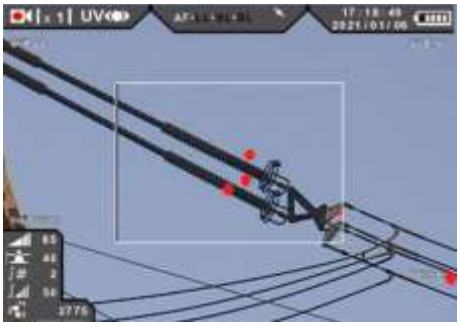


Fig. 6. Ultraviolet image-2 of a Double-Tension string

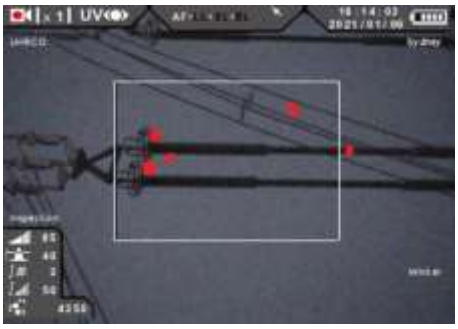


Fig. 7. Ultraviolet image-3 of a Double-Tension string

III. Type Test Report

A voltage 10% above the nominal phase-to-earth voltage shall be applied to the phase conductor. For a nominal 400-kV line-to-line system, the phase-to-earth RMS voltage is $400/\sqrt{3} \approx 231$ kV, and the highest system voltage is typically taken as $1.1\times400/\sqrt{3} \approx 254$ kV RMS. The DEWA requirement of 300 kV for corona extinction is therefore an independent acceptance criterion rather than a direct conversion from nominal system voltage, and it applies to AC RMS test voltage under positive polarity. The minimum corona extinction voltage shall be 300 kV. Corona extinction and RIV criteria follow IEEE Std 1313.2-1999 [1].

Utility standards do not specify the type of corona discharge for determining the corona extinction voltage whether positive or negative. However, the standard states that visible corona formation shall not occur at voltage below 10% in excess of the nominal phase to earth voltage [2].

A negative corona is seen as a glowing blue light, whereas positive corona is seen as white, although many of the emissions are in the ultraviolet spectrum and not visible to the naked eye.

A series of tests was repeated for the affected insulator units as documented in type-test report no. 11724/A/21 [3] for V-Jumper string and report No. 11724/B/21 for double tension strings.

Three sample categories were selected:

- polluted insulators taken from service
- polluted insulators taken from service after cleaning with tap water
- new insulators

Three specimens were tested for each category (polluted, cleaned, and new), giving a total of nine insulators. Polluted samples were retrieved from service and cleaned using tap water without detergents. All tests were performed at the EB Rebosio laboratory in 2021. Acceptance limits were: positive corona extinction ≥300 kV, negative corona extinction ≥200 kV, RIV ≤100 µV at 1 MHz, lightning impulse withstand ≥1050 kV, and wet power-frequency withstand ≥650 kV. Polluted samples were tested in both as-received and cleaned conditions; "clean-condition tests" refers specifically to the cleaned and new samples.

The tests evaluated corona extinction voltage, radio interference voltage (RIV), dry lightning-impulse withstand voltage, and wet power-frequency withstand voltage. All three samples met the specified acceptance criteria. Figs. 8 and 9 show the laboratory corona observations.

As per type test report, minimum positive corona extinction voltage for V-Jumper suspension string was 370 kV and for Double tension string is 302 kV. The minimum negative corona extinction voltage for V-Jumper suspension string is 207 kV and for Double tension string is 275 kV. The DEWA acceptance requirement of 300 kV applies specifically to the positive-polarity corona extinction voltage, as stated in [2]. Negative-polarity extinction voltages are evaluated separately and may be lower, provided that visible corona, UV emissions, or RIV activity do not occur below the specified positive-polarity threshold. Corona inception voltage refers to the point at which discharge begins, whereas corona extinction voltage refers to the point at which discharge ceases during voltage reduction.



Fig. 8. Ultraviolet image of a V-Suspension string at Type Test



Fig. 9. Ultraviolet image of a Double Tension string at Type Test

IV. Electric-Field Simulation Test

As shown by the attached contours plot in Fig. 10 the electric-field values are below the limits. The reported electric-field magnitude at the interface between the energized end fitting, housing, and fiberglass rod was below 3.5 kV/cm.

The clean-condition analysis suggests reduced corona risk under the modelled assumptions.

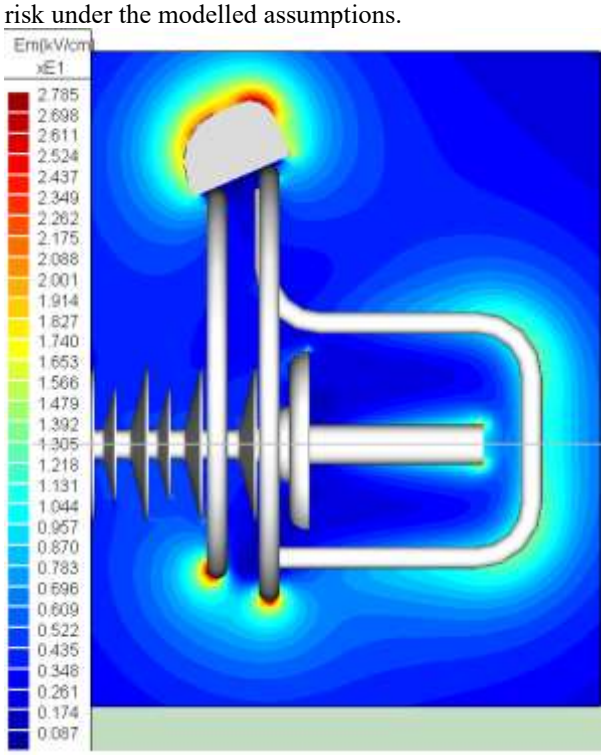


Fig. 10. Electric-field magnitude for insulator model G006400M-Z equipped with arcing ring F0710023.

The contour legend multiplier of $\times 10^1$ has been verified. The global maximum electric-field magnitude in the model is 27.85 kV/cm at the metallic edge of the energized end fitting. The reported <3.5 kV/cm value corresponds to the sampling point located at the housing–fiberglass rod interface, where the field is significantly lower. The original numerical values from the simulation are: 27.85 kV/cm (metal edge), 3.42 kV/cm (housing interface), and 1.15 kV/cm (mid-housing).

A. Proposed Conceptual Model for Polluted Conditions

Although a full numerical simulation could not be carried out, the polluted-condition electric-field model was constructed using methods commonly reported in IEEE literature. No numerical FEM solution was executed for the polluted-condition model. The description provided represents a conceptual, literature-based hypothesis intended to illustrate expected field behavior under contamination, rather than computed results or validated FEM output. The aim was to understand how contamination, moisture, and surface wetting change the electric-field distribution along the composite insulator, especially near the energized end fitting where corona was observed.

To represent realistic field conditions, a thin conductive pollution layer was included on the insulator surface. Several studies have shown that even a modest increase in surface conductivity can distort the electric-field and reduce corona inception voltage [4], [5]. In this model, the pollution layer was treated as a uniform film with conductivity values typical of desert or coastal contamination, consistent with earlier FEM studies on contaminated composite insulators [6], [7]. The conceptual model assumes a pollution-layer thickness of 0.2–0.5 mm, surface conductivity between 50–200 µS, and relative permittivity of 3–4. The applied voltage corresponds to 254 kV RMS phase-to-earth. No solver, mesh, convergence criteria, or air-domain dimensions are provided because no numerical FEM run was performed. A two-dimensional axisymmetric model cannot represent non-axisymmetric grading rings or multi-string hardware, and therefore the conceptual model is limited to the rotationally symmetric region near the energized end fitting.

Moisture was also considered, since wetting and drying cycles often create narrow “dry bands” that intensify the electric-field. Published studies has shown that these dry bands behave like resistive gaps, forcing the voltage to drop across a small region and producing strong field enhancement that can trigger corona at normal operating voltages [8], [9]. Dry bands were treated conceptually as regions of increased surface resistance rather than solely as areas of reduced permittivity. In practice, polluted composite insulators exhibit both bulk conductivity (S/m) and surface conductance (S) effects, and accurate modeling requires solving the coupled conductive–dielectric field formulation. No validated numerical implementation is included in this manuscript. To capture this behavior, the model included alternating wet and dry segments along the housing, with the dry band represented as a narrow region of reduced permittivity.

The insulator geometry was simplified to a two-dimensional axisymmetric cross section, which is a common approach when full 3D modeling is not available. Although the complete insulator assembly includes asymmetrical multi-string hardware, the region of interest around the energized end fitting is rotationally symmetric; therefore, the local electric-field behavior can be accurately represented using a two-dimensional axisymmetric model. The energized end fitting was assigned the phase-to-ground voltage, while the opposite end was grounded. Boundary conditions followed standard practice: Dirichlet conditions on metallic parts and Neumann conditions on the outer air domain, consistent with methods used in earlier IEEE FEM analyses [10], [11].

Although numerical results are not presented, the expected behavior of the polluted model can be inferred from published studies. When a conductive pollution layer is present, the electric-field tends to shift outward toward the surface, increasing stress at the housing–end-fitting interface. This effect becomes stronger when moisture is present, especially near the energized end, where droplets or thin films can create localized intensification. Published studies indicate that contamination and moisture can significantly reduce corona inception voltage compared to clean-condition tests; however, the exact reduction depends on pollution severity and environmental conditions [4], [7], [9].

Based on these findings, the polluted-condition model offers a possible explanation that requires numerical and experimental validation for the difference between laboratory type-test results and field observations. The insulators passed all clean-condition tests, but the environmental conditions on the line—dust accumulation, humidity, and intermittent wetting—likely produced electric-field concentrations that were not captured during laboratory evaluation. This aligns with the corona activity observed near the energized end fitting and supports the need for improved field control, such as the use of grading rings.

V. Comparison of Existing Insulators and Strings

A comparison was made between the proposed assemblies and the existing assemblies, using drawings and site photographs. Table 1 compares insulators which were used and manufactured by LAPP and insulator strings by Mosdorfer [12], with the same conductor type. The main difference is the make between the proposed and existing insulator units (both by Mosdorfer). The main difference is the make of insulators. Existing assemblies used LAPP composite insulators with Mosdorfer hardware, whereas the proposed assemblies use EB Rebosio composite insulators with Mosdorfer hardware. Both configurations employ the same conductor type. The insulator models examined were LAPP type LR400 and EB Rebosio type G006400M-Z.

The proposed configurations include a grading ring. In the photographs, the rings visible on existing assemblies are arcing rings, whereas the proposed assemblies include grading rings designed to reduce peak electric-field intensity. All photographs were taken in January 2021 at the same site and represent existing installations; they do not depict completed future installations or retrofitted configurations. This grading ring was absent from the existing configurations examined.

The compared configurations are shown in Figs. 11–18.

TABLE I
SPECIFICATIONS OF PROPOSED AND EXISTING INSULATOR STRINGS

Parameter	Proposed	Existing
Creepage distance	23100 mm	23200 mm
Arcing distance	5625 mm	5616 mm
Grading ring	Yes	No
Hardware manufacturer	Mosdorfer	Mosdorfer
Insulator make	EB Rebosio	EB Rebosio

A. Proposed 400-kV overhead transmission line



Fig. 11. Proposed Double-Tension String



Fig. 12. Grading Ring



Fig. 13. Proposed V-Jumper suspension String



Fig. 14. grading ring

B. Existing 400-kV overhead transmission lines

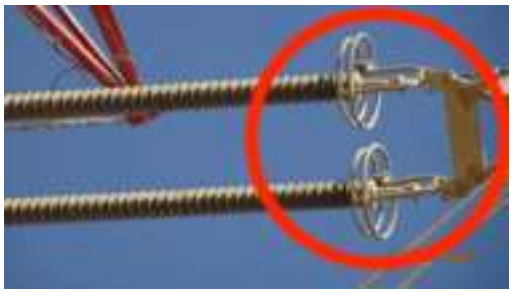


Fig. 15. Existing Double-Tension Insulator showing that there is no grading ring



Fig. 16. Existing V-Suspension Insulator



Fig. 17. Existing V-Suspension Insulator showing that there is no grading ring

C. Reference Quadruple-Tension String Used in Saudi Arabia



Fig. 18. Quadruple Tension String showing that there is no grading ring

VI. Conclusion

Field inspections carried out on multiple 400-kV circuits showed a consistent pattern: corona activity was concentrated at the energized end of the composite long-rod insulators, and the dark surface spots observed on the housings were consistent with discharge activity under service conditions. Ultraviolet imaging localized emissions near the energized ends, and this behavior was repeated across suspension, tension, and jumper configurations.

Although all laboratory type tests were successfully passed—including corona extinction voltage, RIV, lightning impulse, and wet power-frequency withstand—the clean-condition results did not reflect the environmental stresses present on the actual line. Studies have shown that pollution layers, moisture films, and dry-band formation can reduce corona inception voltage by 20–40% compared to clean-condition thresholds [4], [7], [9].

This aligns with the field observations: the insulators performed correctly in the laboratory, yet developed corona once exposed to desert dust, humidity cycles, and conductive contamination. However, dark surface spots and UV emissions alone do not exclude alternative causes such as manufacturing defects, mechanical abrasion, or localized insulation damage. A definitive root-cause determination would require surface examination, pollution-severity measurements, and correlation of discharge locations with material condition. Field ageing behavior of composite insulators has been documented in CIGRÉ TB 815 [13].

The polluted-condition FEM model, constructed using established IEEE methods, provides a reasonable explanation for this discrepancy. When a thin conductive pollution layer is present, the electric-field shifts outward toward the insulator surface, increasing stress at the

housing–end-fitting interface. Moisture further amplifies this effect, especially near the energized end, where droplets or partially wet regions can create localized intensification. Even without numerical output, the expected behavior of the polluted model matches the corona signatures observed in service and supports the conclusion that environmental contamination may have contributed to discharge activity; the available evidence does not exclude other causes.

A comparison of existing and proposed insulator assemblies showed that most of the current 400-kV configurations rely solely on arcing rings, with no grading rings installed. IEEE FEM studies demonstrate that grading rings can significantly reduce peak electric-field intensity at the energized end fitting, improving field uniformity and lowering the likelihood of corona under polluted conditions [10], [11]. The proposed assemblies, which include grading rings, may improve field control, subject to comparative modeling and testing. This comparison is qualitative and does not constitute a matched quantitative assessment under identical geometry, material, and environmental conditions. No FEM results are provided to demonstrate proven improvement or retrofit effectiveness.

Overall, the investigation indicates that the insulator design is technically sound under standard test conditions but not fully optimized for the environmental stresses present on the network. The findings support the adoption of grading rings on future installations and suggest that retrofitting existing lines may help reduce corona-related surface degradation. For long-term improvement, future work should include full 3D FEM simulations, detailed pollution severity mapping, and periodic Ultraviolet/infrared diagnostic surveys to better understand how environmental factors evolve over time and how they influence electric-field behavior on composite insulators.

Conflict of Interest

The author declares no conflict of interest in the publication of this research article. All photographs and test reports are used with permission from the respective organizations. The author confirms sole responsibility for the content and analysis and affirms that the affiliation listed is current.

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Disclaimer

The findings, interpretations, and conclusions presented in this paper are based solely on field observations, diagnostic measurements, and publicly available technical documentation. The mention of specific manufacturers, utilities, or equipment types is for technical clarity and does not imply endorsement, criticism, or attribution of responsibility. All referenced test reports remain the property of their respective organizations. The organizations named in this article did not participate in its preparation and do not necessarily endorse its findings. The author assumes full responsibility for the analysis and opinions expressed in this work.

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