

10131
B2 OVERHEAD LINES
1 - Interconnection of Large Loads

Ultra-High Voltage Insulator String Design- 735kV/765kV Electric Field & Pollution Mitigation

Alex MATTE Sediver Canada & USA Canada Alexandre.matte @sediver.com	Damien LEPLEY Sediver R&D Center France Damien.lepley @sediver.com	Mathieu HELIEZ Sediver High Voltage Lab France Mathieu.heliz @Sediver.com	Frédéric DELHUMEAU Sediver R&D Center France Frederic.delhumeau @sediver.com
---	--	---	--

SUMMARY

With a growing interest in developing new Ultra-High Voltage (UHV) transmission lines across North America, much work has recently been undertaken by utilities as well as by hardware and insulator manufacturers, to develop new string configurations for applications operating at or above 735kV AC.

Standards committees and industry working groups have undertaken to establish permissible electric field tolerances in the evaluation of high voltage insulator string designs. Their evolution over time calls for a dual-faceted approach in understanding an insulator string design's suitability and reliability over time, especially in polluted environments.

This paper details the evaluation of various insulator string designs utilizing both computational finite element analysis to help evaluate electric field distribution and the validation of those simulations by conducting full-scale laboratory testing. Additionally, pollution tests, intended to ensure a design's real-world reliability, are discussed.

KEYWORDS

Ultra-High Voltage, 735kV, 765kV, Corona, electric-field, e-field, pollution

1 Introduction

Sediver's Bazet High Voltage test lab has long conducted RIV/Corona and pollution testing for utilities and hardware manufacturers as part of their efforts to validate the suitability of new insulator string designs. But whereas in years past where the focus was often on lower voltages, a surge in interest in 735kV and 765kV applications [1] has recently brought to light many of the common design practices as there's often more focus and attention applied in the designs of this voltage class [2]. This paper compares finite element studies performed on different 765kV string designs and reveals significant performance differences, all of which were subsequently proven during lab tests.

2 Insulator String Assembly Electric Field Comparisons

2.1 Methodology and Simulation Framework

The finite element simulation tools available today enable the assessment of electric field distribution and associated corona performance of complete insulator string assemblies, for both cap-and-pin and composite technologies. Depending on the objective of the study, different modelling strategies can be adopted. Typically, either the metallic fittings are represented with a high level of geometrical detail and fine meshing while the insulators are simplified, or conversely the insulating profile is modelled in detail and the fittings are approximated.

In all cases, the simulation should consider the complete assembly configuration, including tower geometry, conductor arrangement, and electrical clearances, since these factors can significantly affect the resulting electric field distribution.

The numerical simulations were worked out using the latest version of COMSOL Multiphysics software, in particular the AC/DC module specialized in low-frequency electromagnetics modelling and computation. The computation was based on the Electric Currents formulation with Current Conservation in the (low) frequency domain (50 Hz – 60 Hz for this study) and using the so-called Finite Element Method (FEM):

$$\begin{aligned}\nabla \cdot \mathbf{J} &= 0 \\ \mathbf{J} &= \sigma \mathbf{E} + j\omega \mathbf{D} \\ \mathbf{E} &= -\nabla V\end{aligned}$$

With $\mathbf{E}$ = Electric field, $\mathbf{J}$ = Current density, $\mathbf{D}$ = Electric displacement field, V = Electric potential.

The boundary conditions were applied as follows:

- A potential (kV) corresponding to the single-phase voltage of the line was applied to the volume of the conductor bundle and of all the metal insulator and conductor fittings, arcing protection devices connected to this bundle at the live end.

- Grounding condition i.e., potential equal to 0kV was applied to the tower mockup and to all the metal insulator and arcing protection devices connected at the ground side.
- For numerical simulation with toughened glass insulator units, a floating potential condition was assigned to each volume of each end metal fitting (cap and pin) of each insulator unit.

CIGRE Working Group B2.80 was established to develop guidelines for performing numerical simulations on insulator units, whether cap-and-pin or composite, either as part of a complete string or considered individually in HVAC applications. These guidelines do not assess the global RIV or corona performance of complete assemblies; instead, they provide a consistent framework for analyzing local electric field stresses at the insulator level. For this reason, the working group intentionally limited the scope of this work to single-phase studies and excluded the influence of adjacent phases, as well as large-scale boundary effects such as tower reflections and conductor-to-ground distances.

From a design perspective, the definition of electric field acceptance criteria evolved from conductor-based formulations, historically derived from Peek's law, toward more specific limits adapted to composite insulators, as introduced by EPRI and STRI studies [3], particularly as regards water drop induced corona (WDIC). For toughened glass insulators, such surface-related phenomena are not considered critical, as they do not result in degradation processes that could eventually lead to insulator failure. Consequently, for this technology, the relevant design criterion remains the electric field magnitude at the surface of metallic fittings, which governs corona inception in air.

It should be emphasized that these acceptance criteria are currently the subject of extensive discussions within the community. Recent developments, including the ongoing work of CIGRE WG B2.80, tend toward a simplification and a relative relaxation of the original limits established by EPRI [4] and STRI [5] as seen in Table 1:

Table 1 – Evolution of the Electric Field Assessment Criteria (kV/cm)

Location	EPRI/STRI 2015	CIGRE TB 919 (WG B2.57) 2023	IEC 61109 2015	Polymer / Composite	Ceramic cap & pin
Housing sheath trunk sheath surface	$E_{max} \leq 4.2$ (magnitude, 0.5-1mm from surface)	$E_{max} \leq 4.2$ (tangential) averaged for 10mm	$E_{max} \leq 4.2$ (tangential) averaged for 10mm	Applicable	N/A
Over-molded Sealing surface	$E_{max} \leq 3.5$ (magnitude) at triple point			Applicable	N/A
“Exposed” Sealing surface		$E_{max} \leq 3.5$ (tangential) $E_{max} \leq 8.0$ (normal)	$E_{max} \leq 4.2$ (tangential) averaged for 10mm $E_{max} \leq 8.0$ (normal)	Applicable	N/A
Corona /grading ring & end fitting metal surface	$E_{max} \leq 18$ (magnitude)	$E_{max} \leq 18$ (magnitude)	$E_{max} \leq 18$ (magnitude)	Applicable	Applicable
Other metal fittings surface	$E_{max} \leq 21-22$ (magnitude)	$E_{max} \leq 21-22$ (magnitude)	$E_{max} \leq 21-22$ (magnitude)	Applicable	Applicable

From a physical standpoint, this evolution raises important questions. Numerical simulations are generally performed assuming idealized environments and perfect surface conditions. Oversimplification of acceptance criteria may lead to an inaccurate evaluation of the insulator assembly design with respect to actual service conditions, especially pollution severity, where aging and surface degradation can significantly alter local electric field distribution.

This gap between simulated conditions and in-service reality highlights the need for careful interpretation of simulation results, particularly when used to support long-term performance assessments of UHV insulator systems, such as those operating at 765kV.

2.2 Comparative Study of 765kV Insulator Assemblies

As a case study, finite-element simulations were conducted on two comparable 765kV insulation assemblies, one incorporating toughened glass insulators and the other with composite insulators. Both configurations consist of a single V-string arrangement supporting a six-conductor bundle.

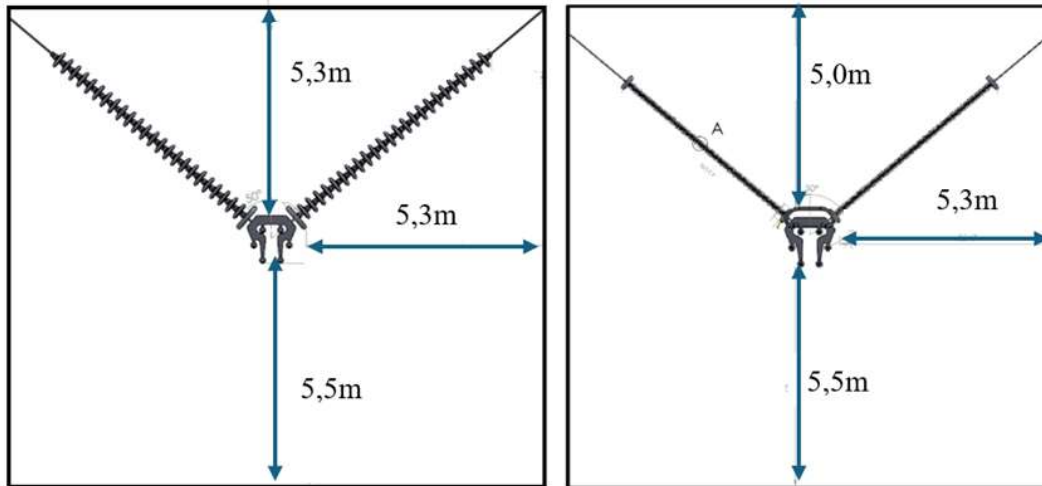


Figure 1 - Configurations used for comparative E-field simulations.

As mentioned in the previous section, when performing this type of analysis, particularly for UHV 765kV arrangements, different evaluation criteria are considered for toughened glass and composite insulator technologies.

2.2.1 Case Study with Toughened Glass Insulator Assemblies

For toughened glass insulators, a preliminary assessment of the electric field distribution is first carried out to evaluate the electrical stress experienced by each cap-and-pin unit along the string (Figure 2a). Subsequently, particular attention is given to the electric field levels in air and at the surface of metallic components, including caps, pins, and the various fittings of the assembly, to identify potential corona activity and regions of high electric field concentration (Figure 2b).

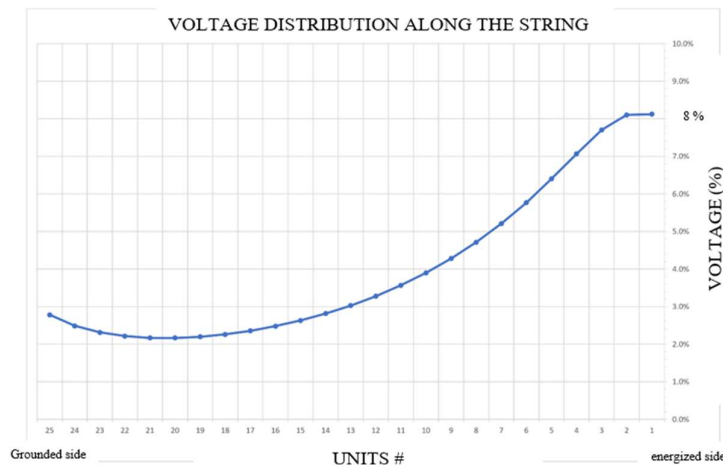


Figure 2a - Voltage distribution along the string of toughened glass insulators.

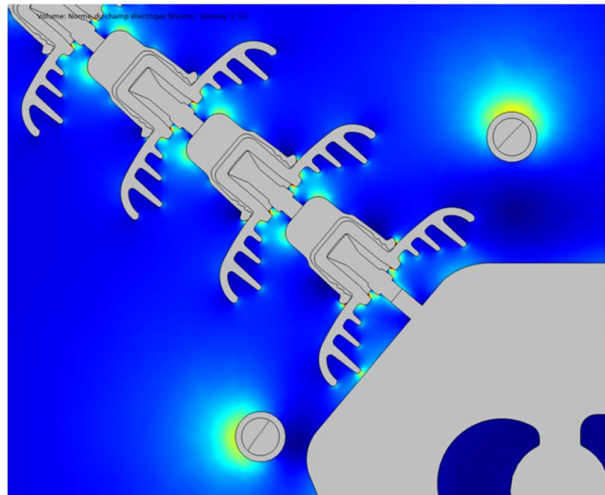


Figure 2b - E-field magnitude at the surface of the components of a toughened glass insulator assembly

2.2.2

For composite insulators, the analysis focuses mainly on the electric field magnitude in critical areas. This includes the tangential field along the profile, especially close to the “triple points” (interfaces between housing, core and metal), and in the vicinity of the metal components.

In addition, the geometry of the different protection devices, including arcing horns and corona rings, as well as their relative positioning, plays a fundamental role in the resulting electric field distribution (Figures 3b). Even small positional variations result in a redistribution of field lines.

Moreover, it is particularly noteworthy that the simplification of the criterion initially proposed by EPRI and STRI for the evaluation of WDIC fundamentally alters the outcome of the analysis, as illustrated in Figure 3a. It should be recalled that this criterion was defined to assess the risk of initiating surface discharges under wet operating conditions.

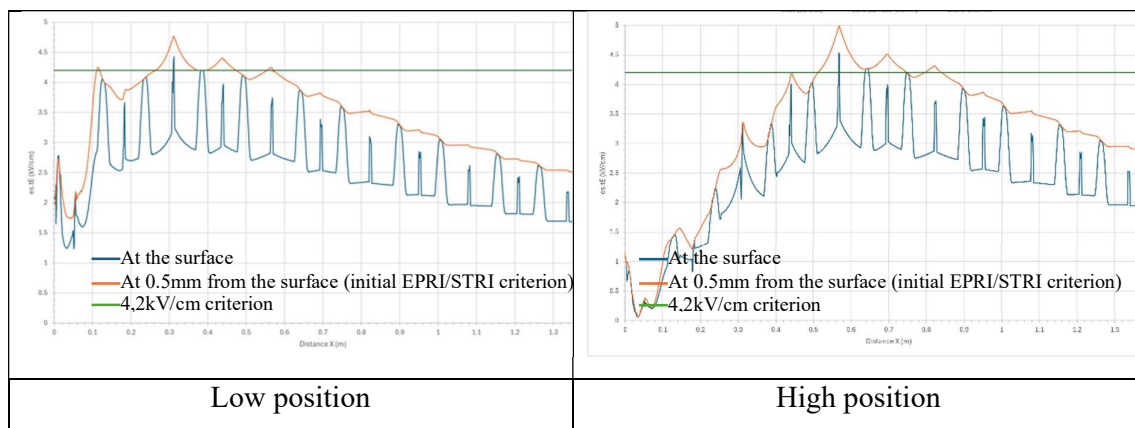


Figure 3a - Tangential electric field

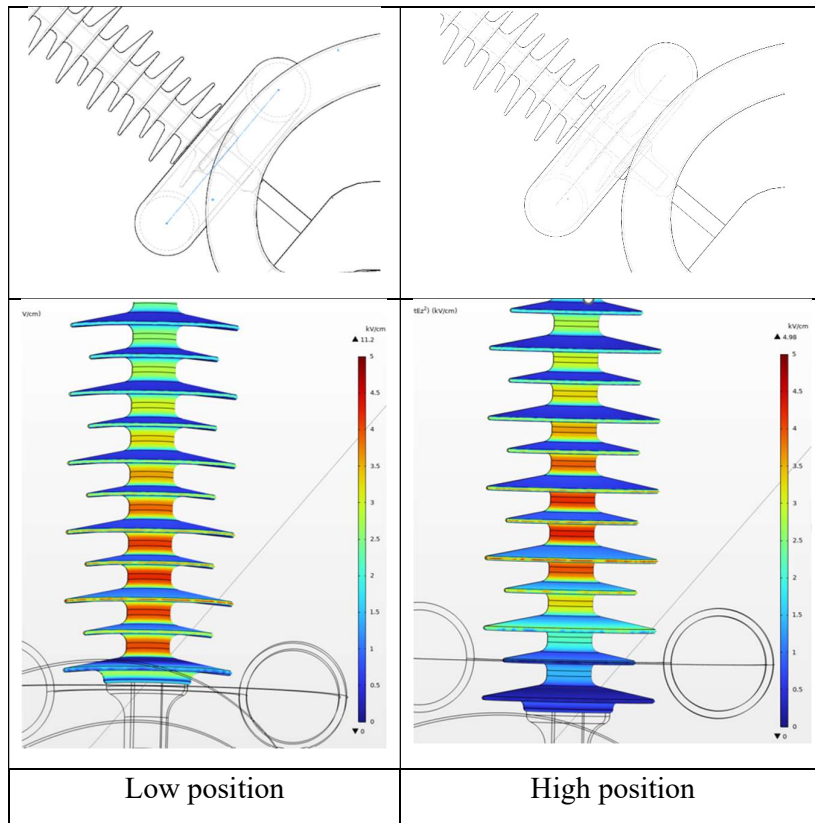


Figure 3b - Comparison of electric field distributions for two grading ring positions of a composite 765 kV assembly.

Electric field optimization at the surface of insulator housing is not the sole consideration governing the design and positioning of grading rings. Indeed, grading rings should not become the elements defining the dielectric performance of the insulator string, especially the arcing distance. Under short-circuit conditions, arc roots must preferentially attach to the dedicated arcing protection devices rather than to the grading rings. This is essential to prevent the full short-circuit energy from being conducted through the crimped regions of the composite end fittings, which could lead to mechanical failure of the insulator.

3 Insulator Assembly Design Laboratory Validation

3.1 From Numerical Simulations to Full-Scale Testing

Finite-element simulations constitute an essential first step in the design of 765kV insulator assemblies, providing valuable insight into the electric field distribution, allowing rapid comparison of alternative configurations, and effectively identifying major design weaknesses or obviously over-stressed areas. However, regardless of the level of detail in the numerical model, all finite element analyses involve geometrical simplifications. Small metallic details, surface roughness, manufacturing tolerances, pin protrusions, interfaces between components

and many other geometric features are generally simplified to maintain reasonable computation times.

Consequently, numerical calculations should primarily be considered as a design and optimization tool rather than a definitive demonstration of performance. The actual behavior of the complete 765kV arrangement can only be validated through full-scale laboratory testing, where all physical characteristics of the manufactured assembly are taken into account, including small geometrical details, surface finish, dimensional tolerances, fitting interfaces, corona ring fabrication, cotter key lengths and shape, and other component features that may affect corona inception and radio interference behavior.

For this reason, numerical simulations and laboratory tests should be regarded as complementary approaches. Simulations enable efficient design optimization, whereas full-scale tests provide the final validation of the selected solution.

3.2 Full-Scale Corona and RIV Test Methods

IEC 61284:1997 [6] defines two alternative approaches for evaluating corona and radio interference voltage (RIV) performance of overhead line fittings and insulator assemblies: the Voltage Method and the Voltage Gradient Method. The standard specifies that the Voltage Method shall use simulated towers, crossarms, earth planes and jumpers representative of service conditions, whereas the Voltage Gradient Method relies on suitable earth screens and an equivalent conductor gradient determined through a calibration procedure.

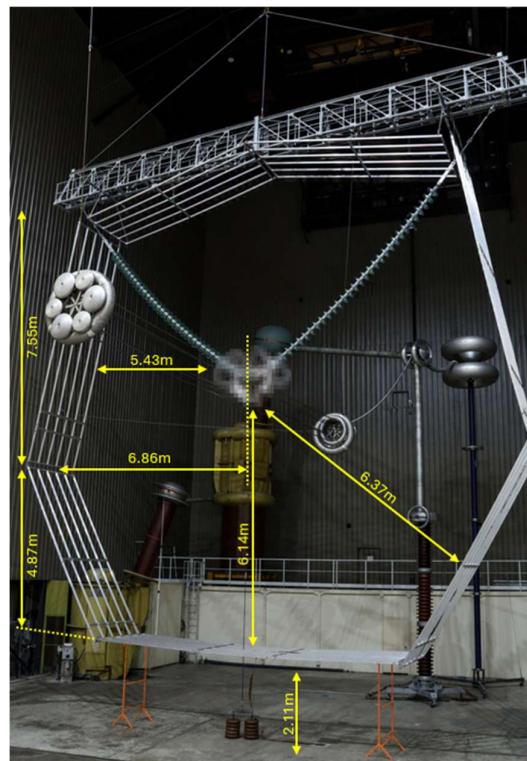


Figure 4 – 765kV full-scale tower window at Sediver's Bazet HV Test Hall.

The Voltage Gradient Method was originally developed to enable testing in laboratories where the dimensions are insufficient to accommodate the complete electrical environment required by the Voltage Method. Because the actual line geometry is not fully reproduced, several correction factors and calibration steps are introduced to derive an equivalent conductor surface gradient from the measured voltage. These additional assumptions inevitably introduce uncertainties, particularly when extrapolating results to very high voltage systems.

It should be noted that, depending on several assumptions, including the selected surface gradient value (E_s), which is often derived from numerical simulations, the altitude correction curve adopted (e.g. Peek, Peterson or Leadville curves as detailed in IEEE 1829-2025 [7]), and the geometry of the test mock-up, the gradient method below may result in test voltages substantially higher than the maximum operating voltage of the transmission line, in some cases exceeding the maximum phase-to-phase service voltage by more than 30%. This could lead to an overdesigned solution intended primarily to satisfy laboratory test requirements.

$$V_R = \frac{E_s}{E_c} \times V_c$$

where

- V_R is the calculated test voltage in kV
- V_c is the positive corona inception voltage observed on calibration sphere in kV
- E_c is the positive corona inception voltage gradient for conductor mounted calibration sphere in kV/m
- E_s is the specified conductor surface gradient for standard of acceptance in kV/m

Figure 5 – IEEE 1829-2025's determination of test voltage using calibration sphere

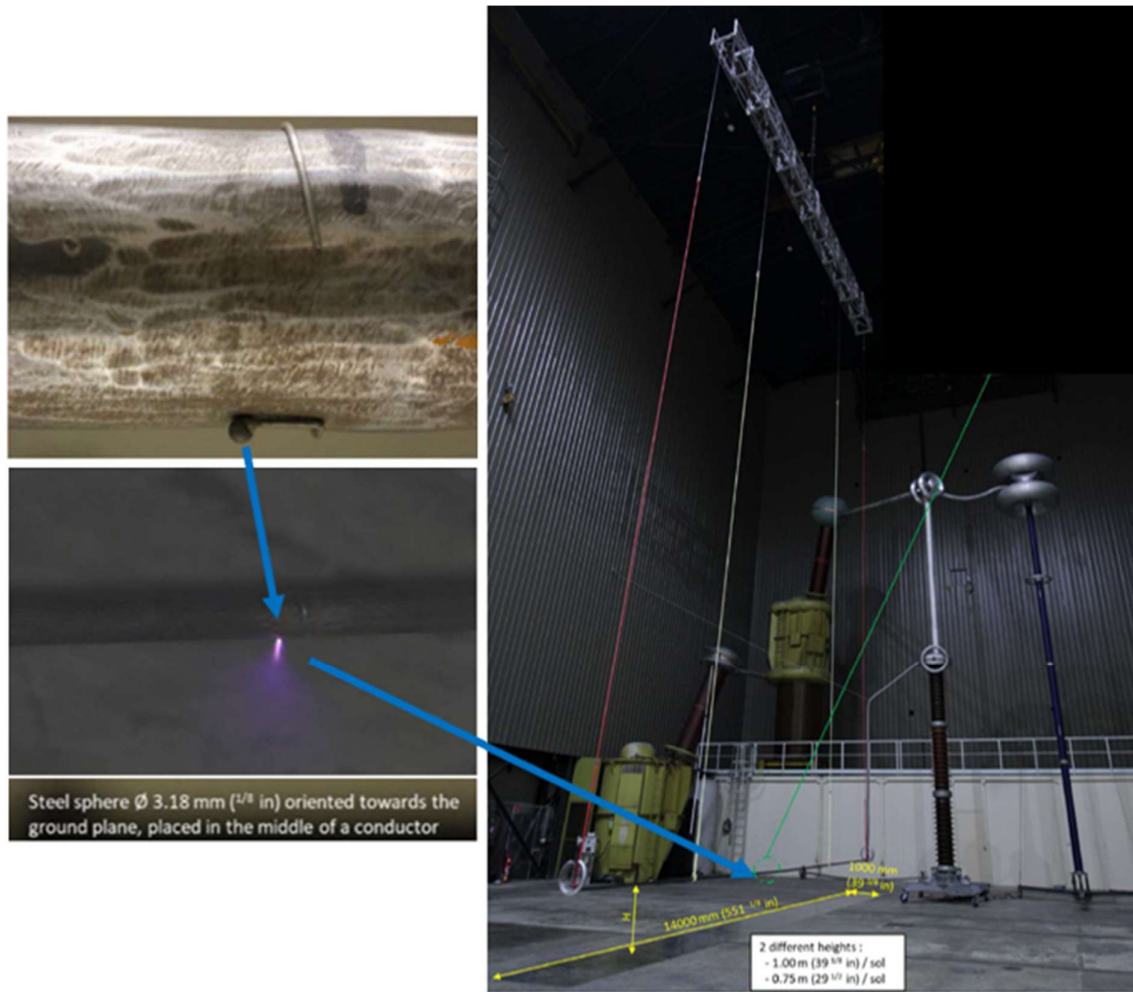


Figure 6 – Gradient method calibration arrangement

In contrast, the Voltage Method allows the complete 765kV assembly to be tested, under realistic electrical conditions. The simulated tower, crossarm and ground plane reproduce the reflection planes present in service. This approach provides a simple and direct assessment of the actual configuration.

Another significant advantage of the Voltage Method is that the complete mechanical arrangement can be verified simultaneously. Full-scale mock-up testing confirms that the insulator assembly integrates properly with the tower design and that clearances remain adequate under representative installation conditions. In addition, lightning impulse and switching impulse tests performed on the same test mock-up enable the verification of the dielectric properties of the design and allows a direct evaluation of the safety margins available with respect to the specified insulation coordination requirements.

3.3 Pollution Performance Assessment

While corona and RIV evaluations constitute an essential step in the validation of a 765kV insulator assembly, they're insufficient on their own to fully assess the suitability of the design. For both cap & pin and long-rod insulators, particular attention must also be paid to the leakage distance and, more importantly, to its effectiveness. The pollution performance of an insulation system is not governed solely by the total leakage distance, but also by the profile geometry, which determines how efficiently this leakage distance can be utilized under service conditions. Consequently, the assessment of the insulator assembly must include dedicated pollution tests with respect to both the operating voltage and the pollution severity of the intended service environment. Such investigations are generally performed on reduced-length strings.

For toughened glass insulators, an efficient approach consists of first determining the pollution flashover performance using a rapid flashover up-and-down procedure B.3.2 of IEC 60507:2013 [8], followed by confirmation tests based on 3 withstand steps according to section 5.2 (salt fog) and 6.6-6.8 (solid layer) of IEC 60507:2013 pollution test recommendations.



Figure 7 – Pollution Test Hall

For insulators featuring hydrophobicity transfer materials (HTM), particularly composite insulators and RTV silicone-coated insulators, pollution testing is inherently more complex due to the hydrophobicity of the housing. IEC 63414:2025 [9] details a procedure developed specifically for hydrophobic surfaces and coated insulators. These methods attempt to account for the hydrophobicity transfer phenomena. In addition, Pollution tests primarily assess short-term electrical withstand performance and therefore do not provide a direct indication of long-term service behavior. Consequently, defining the creepage distance solely on the basis of pollution test results may be insufficient, as it can result in sustained leakage current activity,

progressive loss of hydrophobicity, and ultimately accelerated ageing of the insulating material [10].

3.4 Limitations of Corona/RIV and Pollution Evaluations

Although corona/RIV and pollution tests provide indispensable information regarding the electrical performance of an insulator assembly, it is important to recognize their limitations. These tests provide only a snapshot of the instantaneous performance of the insulator assembly under controlled lab conditions. They do not assess long-term aging mechanisms.

This distinction becomes particularly important when discussing UHV transmission systems. One of the objectives of 765kV line design is to maximize line compactness while maintaining adequate electrical performance and acceptable construction costs. Such optimization inevitably results in higher electrical stress on the insulation system.

For toughened glass insulators, the consequences of these higher stresses are generally limited because the dielectric material is not affected by corona activity or aging. The situation is fundamentally different for polymer insulators incorporating hydrophobic housings. The hydrophobicity of silicone rubber is a complex phenomenon that can be lost under specific conditions but recovered after a period of time if conditions allow it. In addition, these silicones age with time, and consequently, hydrophobicity decreases with time. A decrease in the hydrophobic properties may favor the development of electrical discharges at the surface of the material which will then be subjected to stresses resulting in aging.

An insulator assembly may satisfy all conventional design criteria: electric field limits obtained through finite-element analysis, corona extinction requirements, RIV performance targets, and pollution withstand requirements. Nevertheless, this does not automatically guarantee satisfactory long-term aging behavior of polymer insulators. Excessive local electrical stress may accelerate material degradation, progressively reducing the long-term reliability margin of the system.

For this reason, the evaluation of UHV insulation systems should not be limited to a verification of their initial electrical performance. Long-term material behavior must also be considered as a design criterion.

4 Conclusion

Finite element simulations are powerful tools for the design and optimization of UHV insulator assemblies. They enable rapid comparison of alternative configurations and highlight areas subjected to elevated electrical stress. However, the results remain highly dependent on the modelling assumptions and on the acceptance criteria adopted. It also appears that the ongoing simplification of some electric field criteria should be approached with caution. Numerical calculations are performed under idealized conditions and cannot fully represent the environmental and aging effects encountered in service.

The present work confirms that electric field optimization alone is not sufficient to assess the suitability of a 765kV insulation system. Corona, RIV and pollution performance must be verified experimentally through laboratory testing under representative conditions.

Nevertheless, both numerical simulations and laboratory tests provide only a snapshot of performance under well-defined and controlled conditions. Such evaluations are essential, but they do not fully address long-term behavior in service. The ultimate objective is not simply to achieve satisfactory initial performance, but to ensure that the insulation system maintains its electrical and mechanical integrity throughout a service life that should exceed 50 years. Long-term durability and ageing behavior should therefore remain key design criteria guiding both the selection of the insulator technology and the final design of UHV insulation systems.

Bibliography

- [1] Ashtari R, Guay K, Punjani C, Kadoch A. 11 key design factors for extra high voltage transmission systems [Internet]. Stantec.com. 2025 [cited 2026 Jun 30]. Available from: <https://www.stantec.com/en/ideas/content/blog/2025/11-key-design-factors-for-extra-high-voltage-transmission-systems>
- [2] LEMAN J, Olsen R. Electrical Studies Strengthen Line Design - 765 kV. T&D World. 2026 Jan
- [3] Phillips A, Gutman I. Electric-Field Limits for the Design of Grading Rings for Composite Line Insulators. IEEE Transactions on Power Delivery. 2015;30(3):1110–8.
- [4] Experience with Application Guide for Composite Line. CIGRE WG B2.57; 2023.
- [5] Insulators for overhead lines - Composite suspension and tension insulators for a.c. systems with a nominal voltage greater than 1 000 V - Definitions, test methods and acceptance criteria. IEC 61109; 2025.
- [6] Overhead lines - Requirements and tests for fittings. IEC 61284:1997;
- [7] IEEE Guide for Conducting Corona Tests on Hardware Assemblies for Overhead Transmission Lines and Substations. IEEE 1829-2025.
- [8] Artificial pollution tests on high-voltage ceramic and glass insulators to be used on a.c. systems. IEC 60507:2013;
- [9] Artificial pollution tests on high-voltage polymeric insulators to be used on AC and DC systems. IEC TS 63414; 2025.
- [10] Pigini A. Guide for the Selection of Insulators in Respect of Polluted Conditions, 21st International Symposium on High Voltage Engineering, 2019;