Simulation of electric field: what and what not to expect

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SEDIVER

For composite insulators (usually equipped with grading/corona rings), numerical simulations are commonly, not to say systematically required to ascertain the electric field at three sensitive areas: on the grading/corona ring and end fittings, on the housing surface, and at the triple point where air and housing meet the metallic end fitting. The main purpose is to assess the risk of having deep erosion related to water droplet corona. This degradation is considered as critical because erosion on a composite insulator sheath can go deep down to the fiberglass core and results in brittle fractures or other failure modes.

The situation is very different for toughened glass (or porcelain) cap and pin insulators, with or without RTV coating. The approach described above is usually not considered by end users since the absence of fiberglass core in such cap and pin insulators avoids having these concerns and the only characteristic to consider is the visible corona inception voltage. This corona inception is directly related to the electric field in the air surrounding an insulator string and to the voltage grading along this string.

Sediver has a long experience in E-Field calculation with contributions to CIGRE in the evaluation of E-Field methods as early as the late 1980s where such calculation was still in its infancy. Sediver now uses extensively Finite Element Analysis (FEA) of electric field distribution and voltage grading to validate and secure the design of insulator strings up to the complete assemblies with hardware and fittings. Sediver currently works on COMSOL after having used ELECTRO and COULOMB. Several examples of these works on AC Overhead Lines insulator strings are presented in this paper.

1 FEA Methodology

First of all, it is worth presenting the overall process of a Finite Element Analysis (FEA). This process may be synthesized as follows:

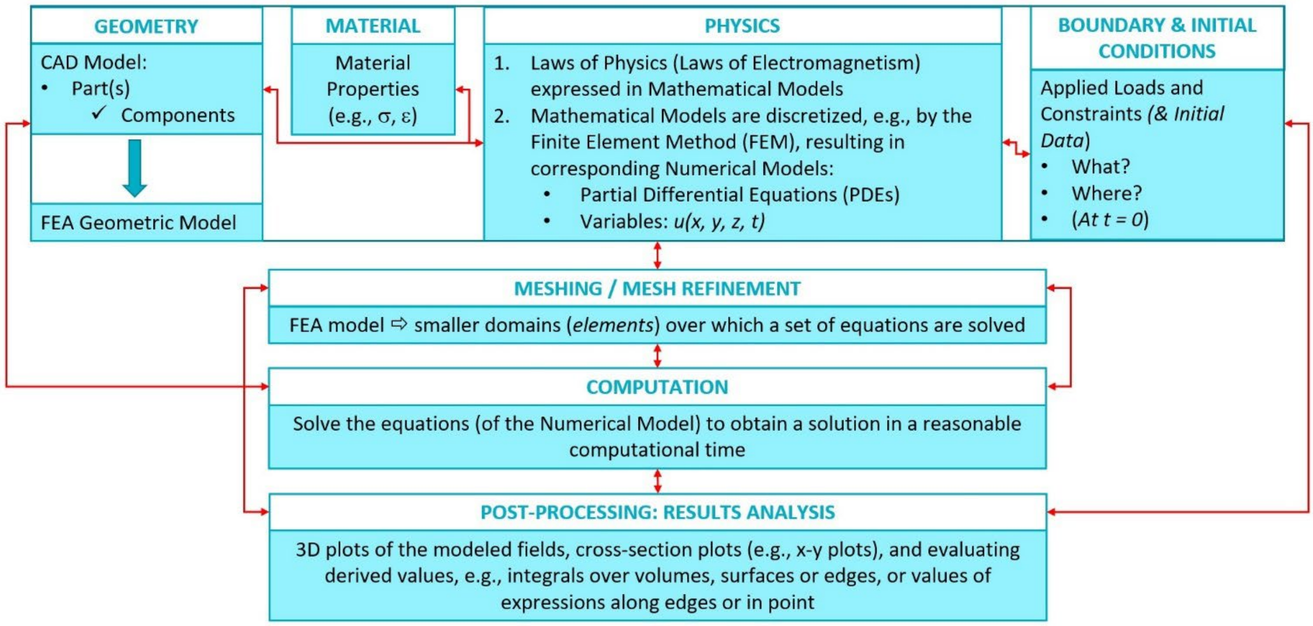

Fig. 1: Overall FEA Process Flowchart

FEA is usually an iterative process: it starts with a simple model that includes the geometry, the material(s), the physics, and the boundary conditions. This model may be step-by-step fine-tuned increasing its complexity and/or level of detail. Each iteration is worked out keeping a balance between two opposing criteria: On the one hand, the model shall be fine or detailed enough so that the computed solution will approach as much as possible the "true solution"; on the other hand, the model shall be coarse or light enough so that the numerical model is able to converge in a reasonable computational time without any error when solving the equations. Red arrows in the above flowchart represent the possible forwards/backwards between the different steps of the process.

The appropriate "physics" shall be defined first. Most of the software solutions available exhibit a large library of physics models. Among all those covered by the fundamentals of Electromagnetics and described by the Maxwell's equations, the following physics[i] maybe be considered and evaluated:

- **Electrostatics**: This is the subfield of electromagnetics describing an electric field due to static (nonmoving) charges. As an approximation of Maxwell's equations, electrostatics can only be used to describe insulating, or dielectric, materials entirely characterized by the electric permittivity. When performing an electrostatics analysis, any conducting materials, typically metals, are first removed from the analysis, and the metallic surfaces are seen as exterior boundaries from the perspective of the dielectric materials.
- **Steady currents**: This analysis is used to compute the steady current flow in highly conductive materials such as metals. An electronic current is driven through a conductor by a difference in the electric potential. The material in a steady currents analysis is completely characterized by its electrical conductivity. When performing a steady currents analysis, any insulating materials are first removed from the analysis and the insulating surfaces are seen as exterior boundaries from the perspective of the conductive materials.
- **Electroquasistatics**: This analysis is a generalization of electrostatics and steady currents in cases where magnetic effects can be neglected. It is only possible to combine the capacitive effects of electrostatics with the conductive effects of a steady currents analysis if the fields are time varying. if there is any time variation in, say, voltages at the boundaries, the total current is the sum of a conduction current and a displacement current. The conduction current density is associated with the electric conductivity,

and the displacement current density is associated with the electric permittivity. Electroquasistatics can be seen as a dynamic version of the steady current equations with an additional contribution from the displacement current.

Two out of these three analyses are of particular interest; typical inputs and outputs for those are presented in the following table:

Inputs	**Geometric Location**	**Electrostatics**	**Electroquasistatics**
Relative permittivity (ε_r)	Volume	X	X
Conductivity (σ) or resistivity (ρ)	Volume	-	X
Electric potential (V)	(Conducting) boundary	X	X
Outputs	**Geometric Location**	**Electrostatics**	**Electroquasistatics**
Electric potential (V)	Volume	X	X
Floating electric potential (V)	Conducting boundary	X	X
Electric field (E)	Volume	X	X

Table 1: Typical inputs and outputs of physics (Non exhaustive)

Various numerical methods have been developed to obtain solutions for electromagnetic field problems. There are two different kinds of solution methods: using either differential equations or the integral equations. The former is known as the domain method and the second is known as the boundary method.

The domain methods are based on differential equations and on discretization of the whole domain by regular grids or elements. The finite difference method (FDM) and the finite element method (FEM) are the most familiar domain methods. Works presented in this paper were based on the FEM.

The complexity of the geometry of a complete insulator strings assembly (set) with fittings shall be thoroughly assessed before performing a FEA.

First, and contrary to a long rod composite (or porcelain) insulator, an insulator string (without hardware) combines multiple parts of different materials and of various and complex shapes with dimensions in the range of a few millimeters or centimeters and resulting in a complete "heterogeneous structure" with dimensions up to more than several meters.

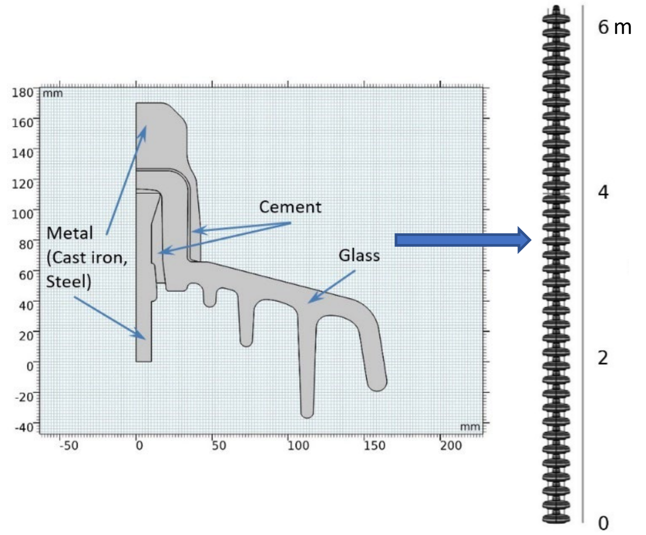

Fig. 2A: Simplified Insulator Unit/String model

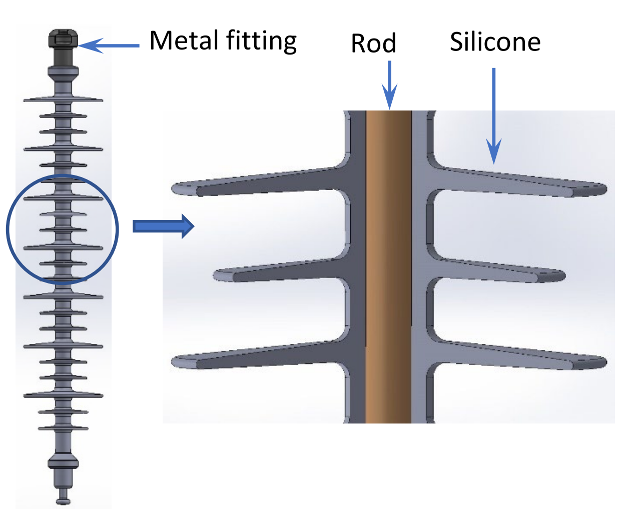

Fig. 2B: Long Rod Composite Insulator model

Some simplifications of this geometric model may become necessary but depend on the objective of the FEA. With regards to the assessment of Electric Field distribution and voltage grading along insulator strings,

- The detailed designs of the ball and socket coupling and of the split pin locking device of the insulator units may be simplified as long as it ensures a continuous voltage distribution.

- All the hardware and fittings constituting the complete assembly may be modeled by simplified but representative metallic parts. However, and whenever used, arcing protection devices (such as arcing horns, rings, rackets) shall be modeled accurately since they have a significant impact on the electric field distribution and voltage grading.
- All the parts that constitute the geometric model, primarily the insulator units, hardware and fittings, may exhibit “singularities”, such as screws, nuts, split pins, sharp angles, sharp edges, recesses… that may result locally in numerical results that do not account for the “real-world behavior”. These “singularities” may be simplified and not considered in the FEA. The FEA will not compute accurately the electric field that could be induced locally around/nearby these “singularities”, which however might induce Corona/RIV activity during laboratory testing or in service if inappropriately designed or manufactured.

As well, a complete insulator set with fittings may combine multiple materials with different characteristics; Typical magnitudes of such properties are illustrated in the table hereafter. Properties of insulating parts, i.e., toughened glass (or porcelain) associated with the cement shall be thoroughly documented or characterized.

Materials	Conductivity (σ) [S/m]	Relative permittivity (ε_r)
Air	0	1
Cement (or Porcelain)	About 10E-4	1 < < 20
Glass	About 10E-12	1 < < 10
Metal	About 10E+6	1

Table 2: Materials properties and typical magnitudes

The geometric model can be meshed automatically by the software as shown in Figure 3 hereafter. The accuracy of the results that can be obtained from any FEA model is strongly related to the finite element mesh that is used. The “physics-controlled” meshing is an option to take into consideration not only the geometry and the materials of the different parts and their components but also the “physics” to solve.

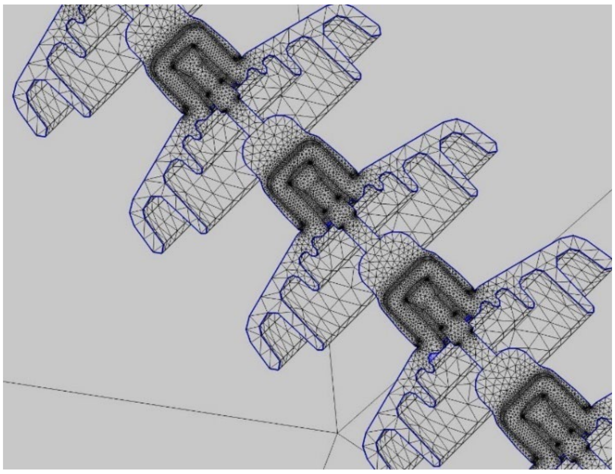

Fig. 3: “Standard” meshing of insulator units

Various techniques such as global or local adaptive mesh refinement can be applied to improve the accuracy. The fineness of the mesh is directly and primarily dependent on the scale and the degree of accuracy of the geometric model.

For FEA on complete insulator set with fittings, the meshing may be refined in all the parts close to the energized conductors, in particular the insulator units and the arcing protection devices close to the energized conductors as shown in Figure 4. The purpose is to achieve more accurate results in the areas where the highest electric field can be expected and where possible corona inception is more likely to occur.

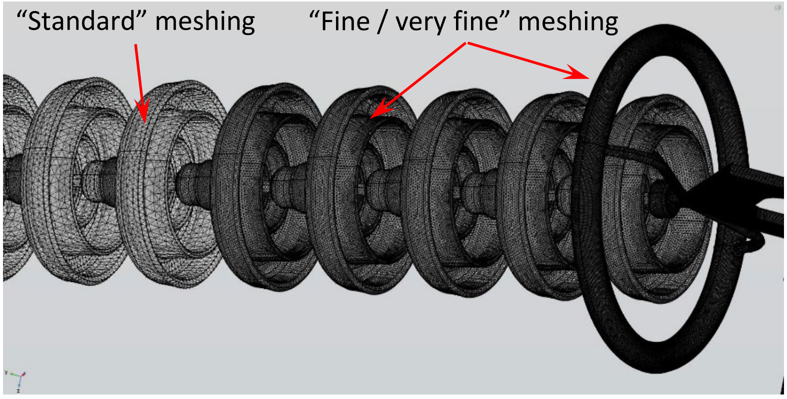

Fig. 4: Meshing adjustment at the bottom of the insulator string

Figures 5A and 5B hereafter show for illustration purpose an example of the complete model of a V-suspension set in a central window of a suspension tower, before and after meshing. Since it is an insulating material (gas), a sphere of air and of “infinite” diameter (or volume) was modeled all around the insulator assembly, conductor bundles and tower model. To ease the numerical computation, i.e. reduce the computation time and the risk of numerical errors, geometric symmetry planes of the actual assembly were considered.

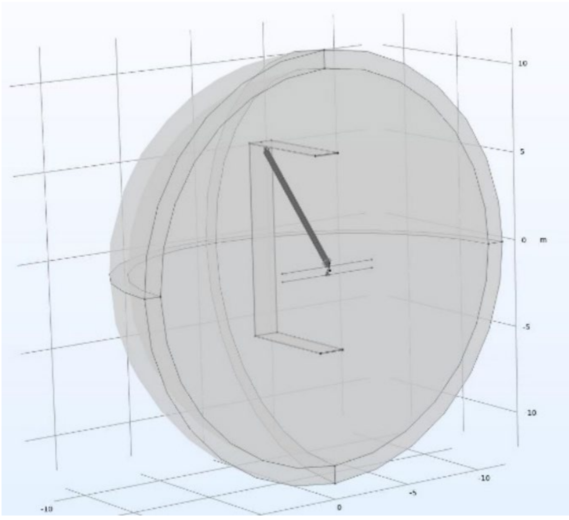

Fig. 5A: 3D model before meshing

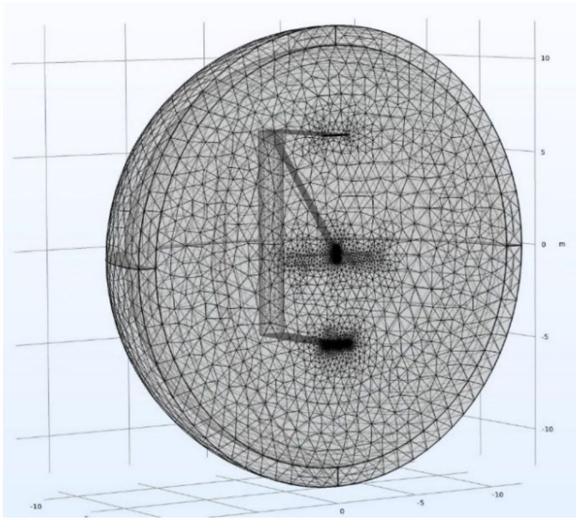

Fig. 5B: Meshing of the entire model

2 FEA Process Validation – Comparison with Laboratory Testing

In order to evaluate its representativeness and accuracy, a FEA was worked out on a simple insulator hardware assembly and the results compared to those obtained by laboratory testing.

The insulator set considered consisted was a single I-suspension string of Nos. 10 units connected with simple fittings to a conductor (modeled by a tube) of a given length and hanged up to a cross-arm. Figure 6A to 6C hereafter show the 3D-Geometric model used in the FEA and the test set up.

The FEA was carried 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 Conservation of Currents in the (low) frequency domain (50 – 60 Hz).

An essential question then arises: What relevant parameter(s) can be considered to compare numerical simulation to laboratory measurement?

- The electric field: It is the primary cause of possible Corona inception, which is associated to the appearance of a conductivity of a gas (i.e. air) in the environment of an insulator set (or a conductor) brought to a high voltage. It is well-known that intense electric fields that may occur at the surfaces of “live” components of the insulator set may lead in some circumstances to ionization and electrical breakdown of the air immediately surrounding these parts. However, the Laws of Physics, and the Mathematical and Numerical models of the software solutions available do not address or account for this phenomenon of air ionization and appearance of such Corona.

Furthermore, accurate measurement in laboratory (or on an operating overhead line) of the electric field distribution around an insulator string is not (or hardly) accessible. Measurement of Corona inception in laboratory is based on examination. Even if some techniques such as light amplifier or Corona camera may be used to have a more accurate measurement, the examination of Corona inception on "actual" parts is strongly dependent on factors such as local shape and dimensions, surface quality… that are not easily addressed by the numerical simulation as it has been implemented.

- The Voltage grading (in kV or % of the applied voltage) along each insulator string of the string. Although it is not covered by any international test standard, this distribution may be both measured in laboratory using a sphere-gap device and obtained from a numerical simulation.

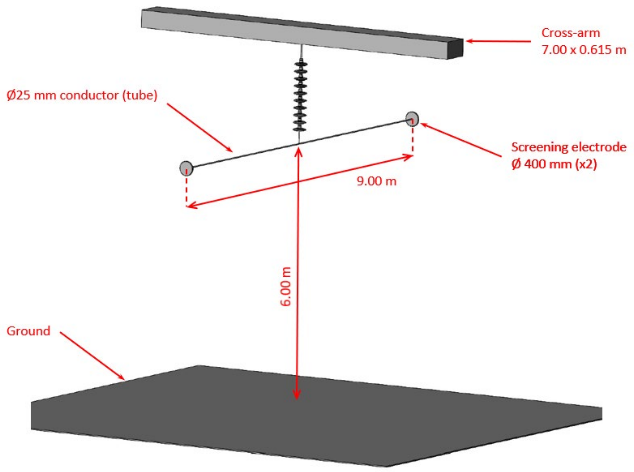

Fig. 6A: Overall view of the FEA model

Fig. 6B: Overall view of the laboratory test set up (SEDIVER C.E.B. High-Voltage laboratory)

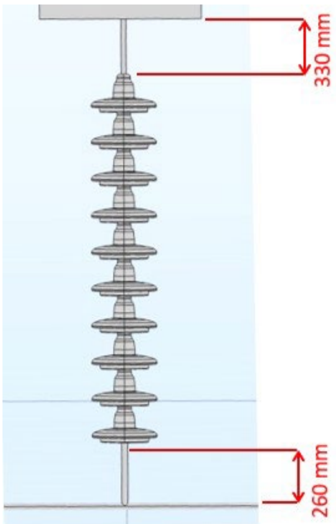

Fig. 6D: Single I-suspension set – FEA model

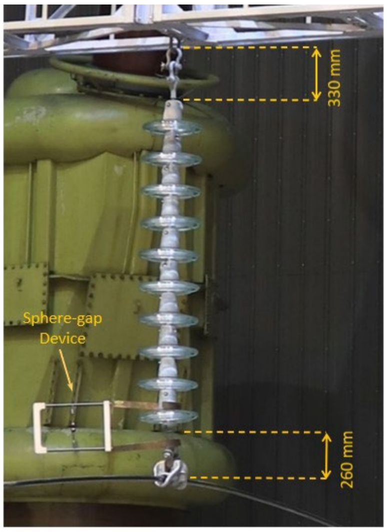

Fig. 6E: Single I-suspension set – Test

Figure 6F shows the comparison of the voltage distribution (in % of the applied voltage) across each insulator unit obtained from the numerical computation (in blue) and by laboratory measurement (in green).

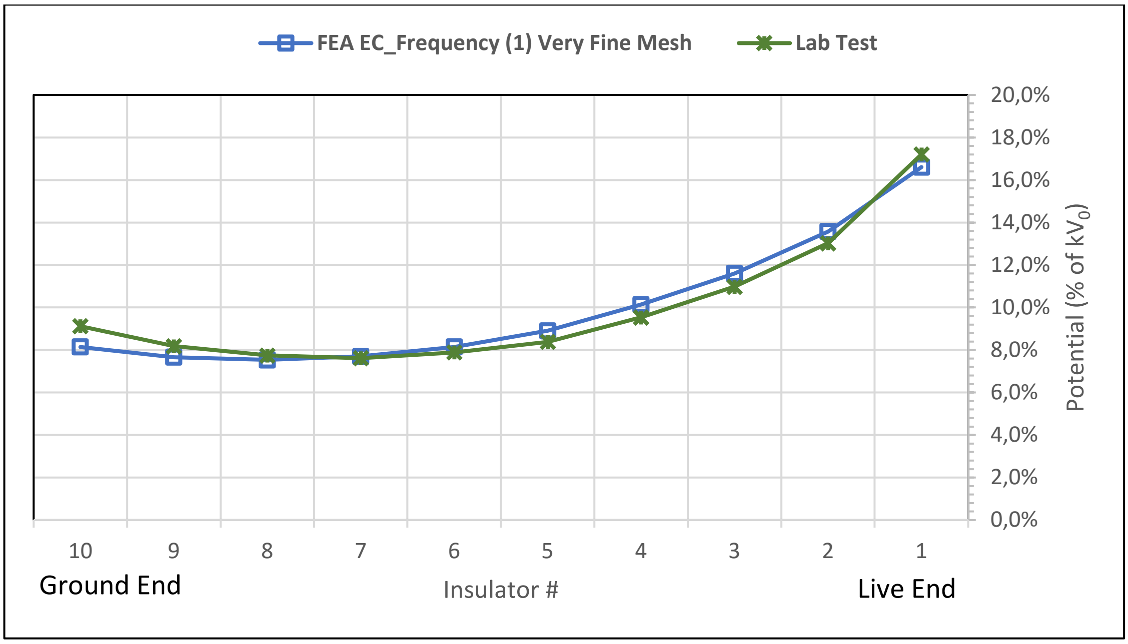

Fig. 6F: FEA Computation vs. Measurement of the voltage grading (% of the applied voltage)

Considering the uncertainty inherent in any test method, this study showed a good consistency and a small difference (i.e. less than one (1) percent) between the numerical results and the experimental ones, which is negligeable.

3 What to Expect:

The use of FEA may be of great benefit to validate and secure the design of insulator sets for an overhead transmission line. Some examples based on real case-studies are presented hereafter.

3.1 Example 1 – Effect of the Protections

A first example illustrates the analysis of the effect of the arcing protection devices at the live end of a V-suspension set. For a given number of insulator unit per string, a given conductor arrangement, comparative simulations were worked out respectively without and with protections rackets or rings.

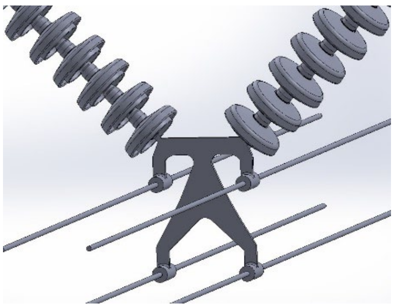

Fig. 7A: No protection

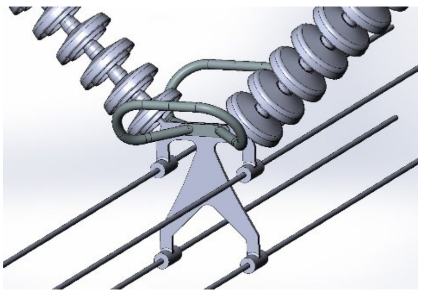

Fig.: Double Rackets

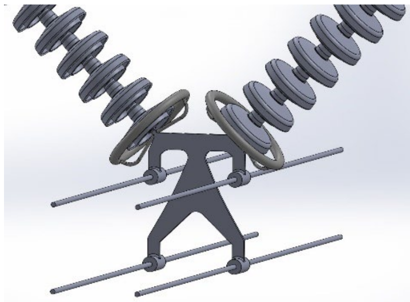

Fig. 7C: Double Rings

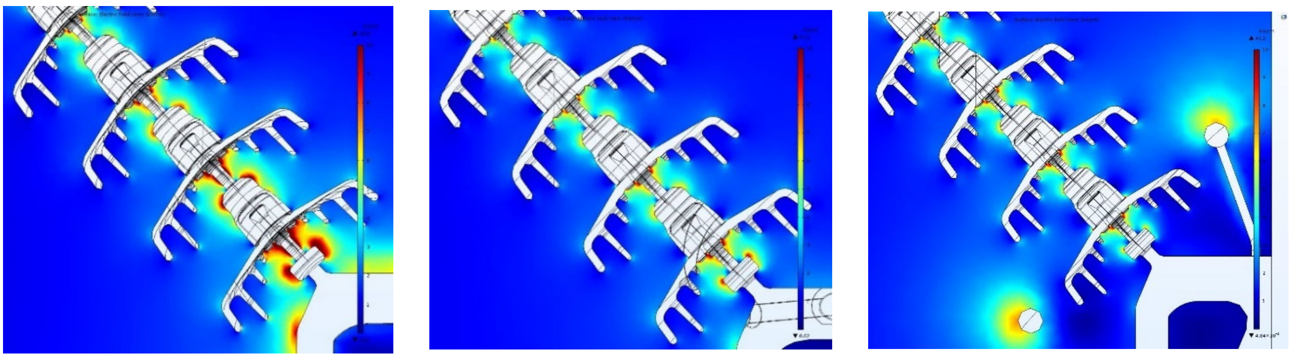

Fig. 8: Comparative views of the E-Field distribution (kV/cm) in the air around the insulator units at live end of the string (Cross-sectional views – Same scale)

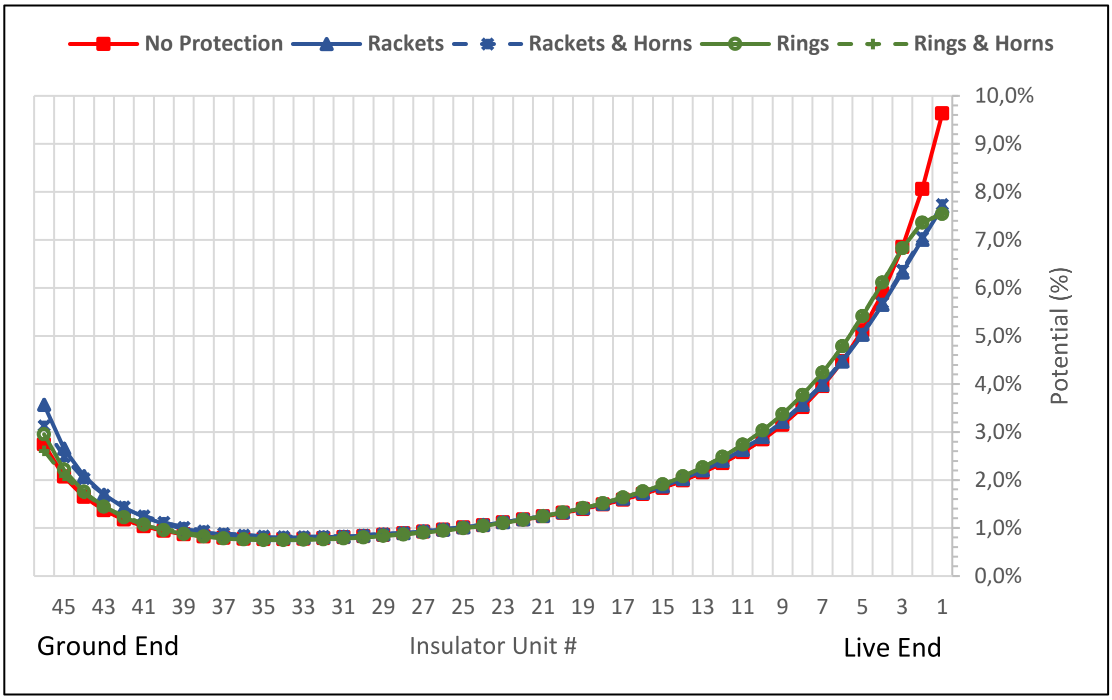

Fig. 9: FEA Computation of the voltage grading – Effect of the arcing protection devices

The computations clearly showed the effect of the protections in the reduction of both E-Field and voltage grading at the bottom sides of the strings. In this particular example, the arcing rings were found slightly more effective than the rackets.

Additional laboratory tests showed a good consistency between areas of highest calculated electric field and examination of Corona inception location.

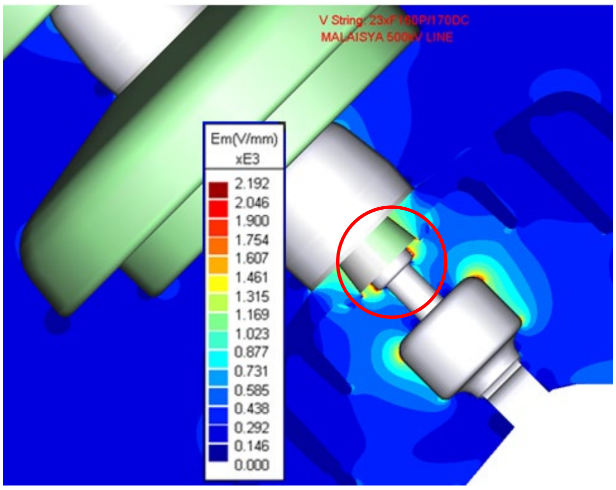

Fig. 10A: 2D-Plots of E-Field in the air on the first insulator unit (No protection)

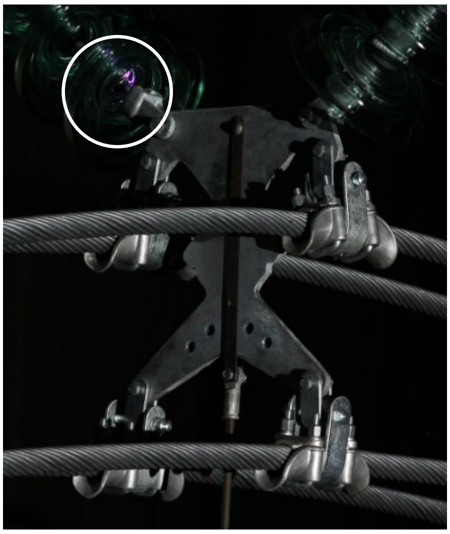

Fig. 10B: Corona Inception observed laboratory test (No protection)

3.2 Example 2 – Effect of the Insulator Number per String

A second example illustrates the effect of the number of insulator unit in a V-suspension string in the lateral phase of a suspension tower. In this example, the V-suspension set is equipped with arcing horns at ground end and arcing rings at the live end. The length of the extension links connecting the first insulator unit (at ground side) to the tower cross-arm is adjusted according to the number of insulator unit in the string so that the overall dimensions (i.e., width and height) of the insulator set are constant and so that the distances of the conductor bundle to the tower (i.e., cross-arms and vertical plane) are constant as well.

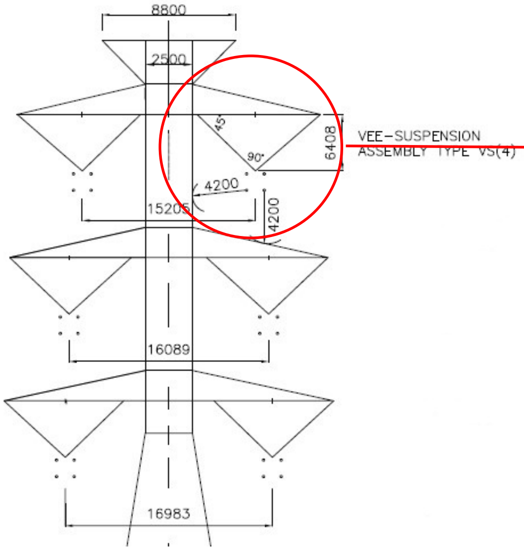

Fig. 11A: Tower Design (Sketch)

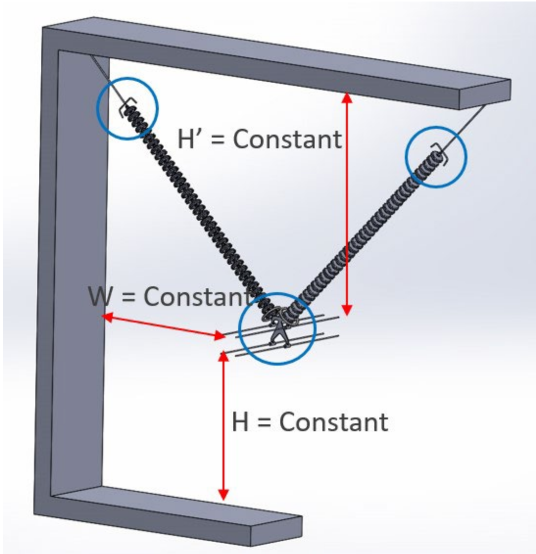

Fig 11B: FEA Geometric Model

From this FEA no significant difference in the E-Field distribution and voltage grading was observed at the live end of the set (close to the conductor bundle). On the opposite and although the values were pretty low, the increase in the number of insulator unit allowed to reduce the electric stresses. This result was confirmed by a voltage distribution test in laboratory.

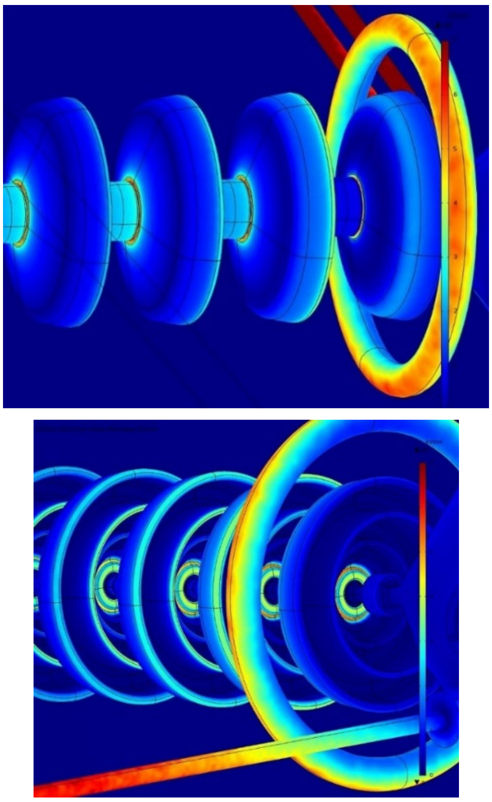

Fig. 12A: N = 38 units

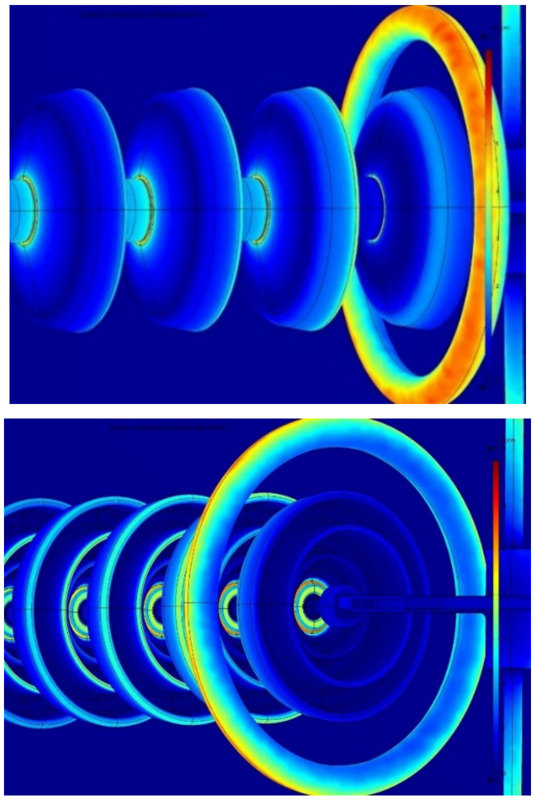

Fig. 12B: N = 46 units

E-Field distribution (kV/cm) on Surfaces at Live End (Top and Bottom views)

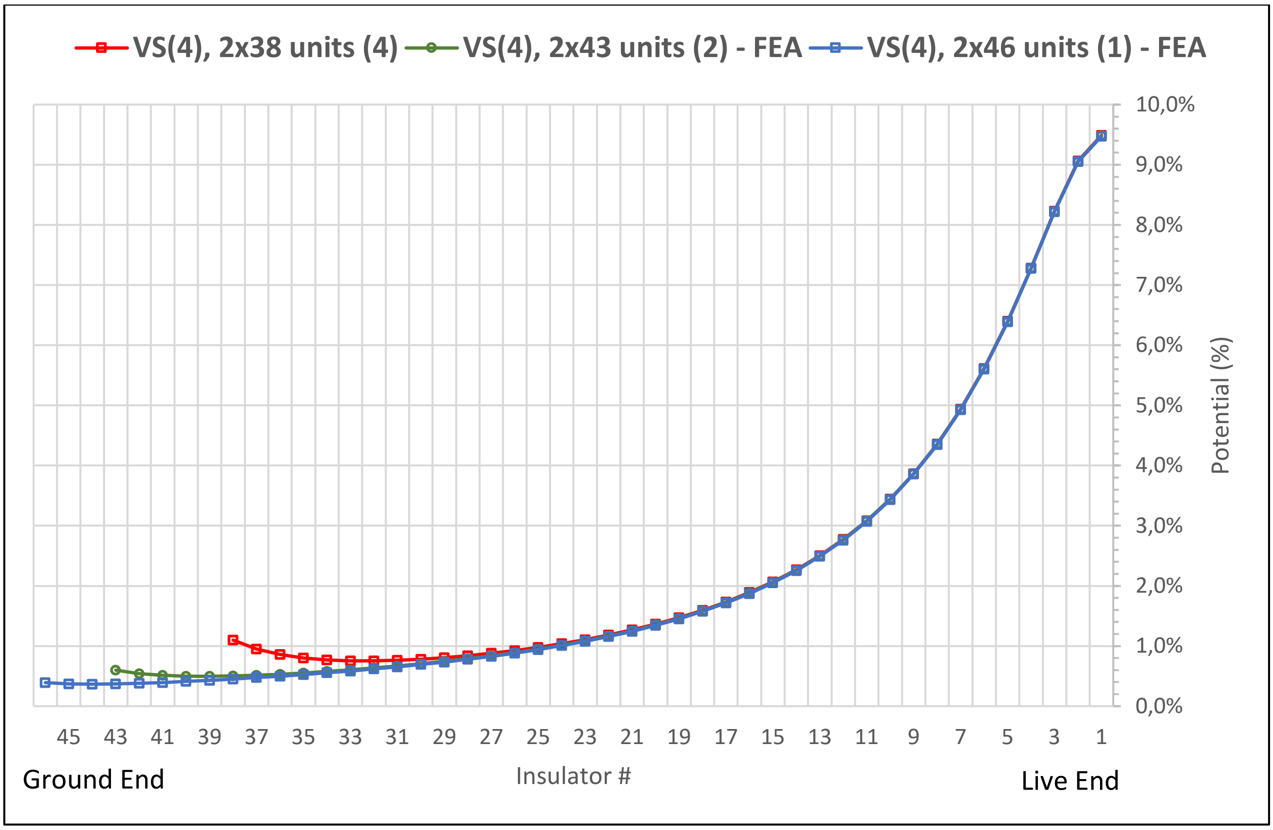

Fig. 13: FEA Computation of the voltage grading – Effect of the insulator unit number (N = 38, 43, or 46 units)

A pretty good consistency in the voltage grading was further observed between numerical simulation and laboratory test.

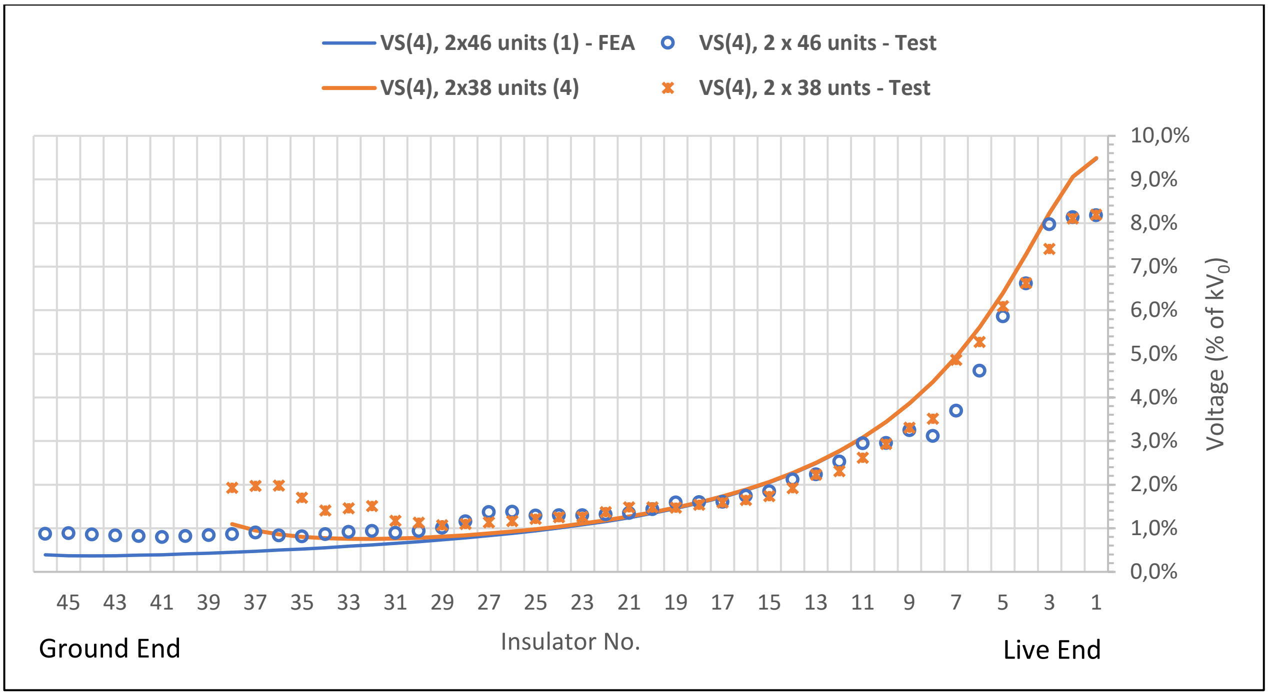

Fig. 14: FEA Computation vs. Measurement of the voltage grading – Effect of the insulator unit number

3.3 Example 4 – Effect of the Conductor Bundle Arrangement

In this example, the influence of the design of the conductor bundle arrangement on the E-Field distribution at the bottom of the insulator strings was studied. For a given V-suspension set, a triple arrangement and a quad one of a conductor bundle of the same spacing were analyzed and compared.

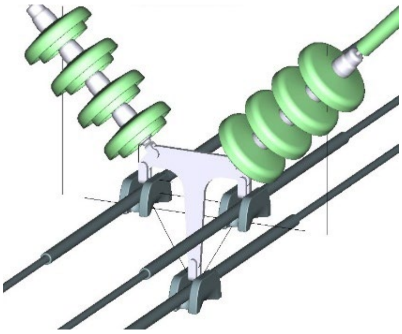

Fig. 15A: 3D Model with Triple Bundle.

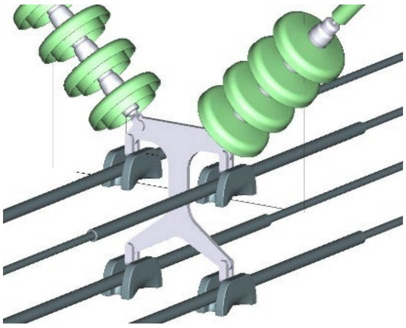

Fig. 15B: 3D Model with Quad Bundle.

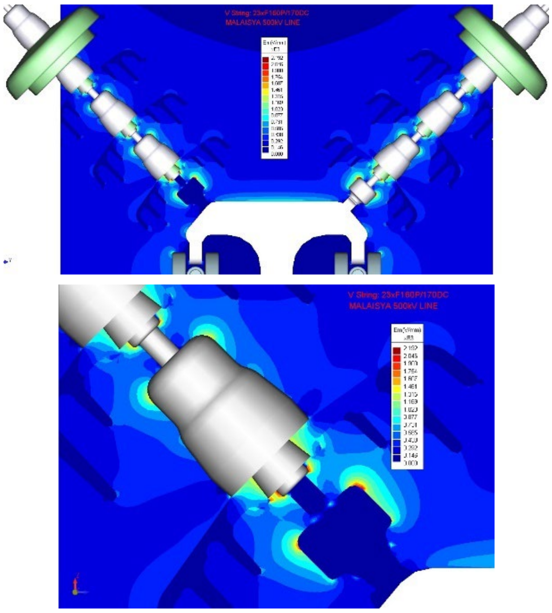

Fig. 16A: 2D-Plots of E-Field in the air at bottom insulators – Triple Bundle

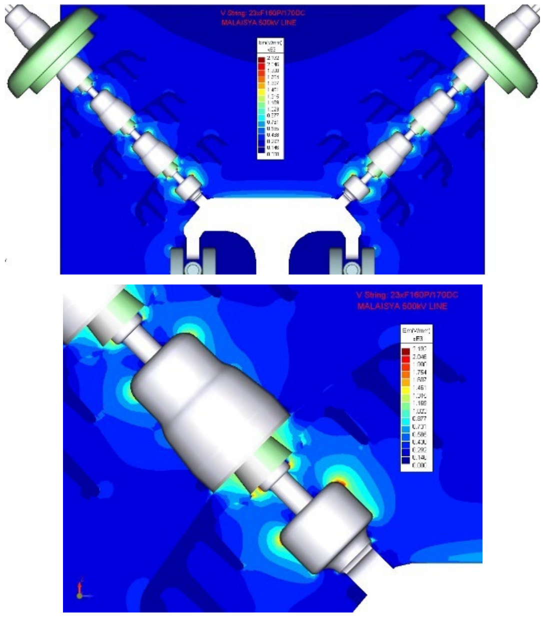

Fig. 16B: 2D-Plots of E-Field in the air at bottom insulators – Quad Bundle

In this example, no significant difference in the E-Field distribution at the bottom of the strings were found. The E-Field is primarily affected by the two uppers sub-conductors of the bundle rather than by the lower one(s).

3.4 Example 5 – Effect of the Tower Grounding (Suspension sets)

In this example, the "grounding" effect of the tower on the voltage distribution (end E-Field distribution) along a suspension insulator string was studied. The aim was to define the appropriate "size" and complexity of the geometric model that is suitable for a representative and accurate FEA. Considering a V-suspension set design with a constant number of units, the following simulations were performed:

1. V-suspension set without attachment fittings (such as extension links) and without tower – See Fig. 17A.
2. V-suspension set with extension links connecting the upper ends of the insulator strings to a horizontal cross-arm – See Fig. 17B.
3. The same model as above but adding a vertical plane simulating the tower body – See Fig. 17C.
4. The same model as above but adding a horizontal plane underneath the conductor bundle, simulating the grounded cross-arm of the lower phase, – See Figure 17D. Two distances (H1 and H2) between the two lower sub-conductors of the bundle and the bottom grounded cross-arm were considered.

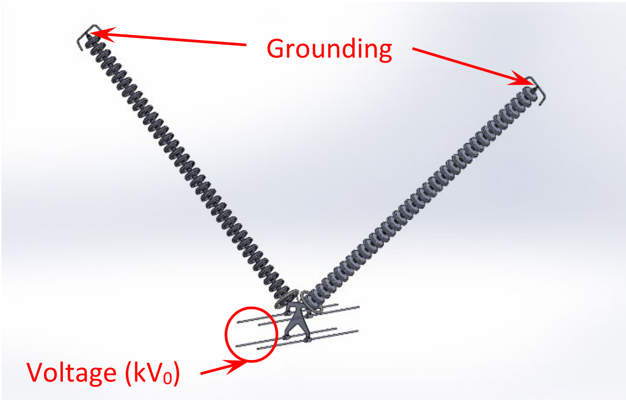

Fig. 17A: V-suspension set model without extension link and without tower.

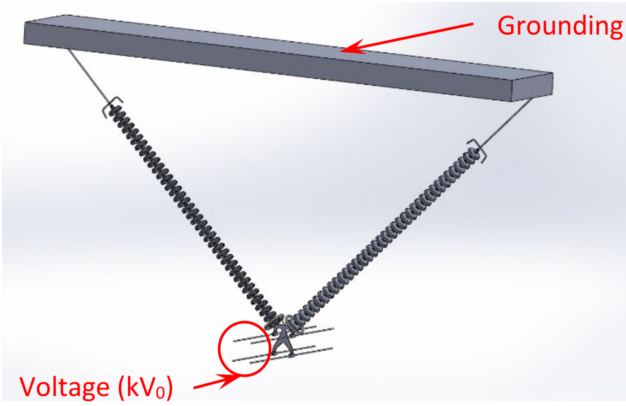

Fig. 17B: V-suspension set model with extension link and horizontal cross-arm.

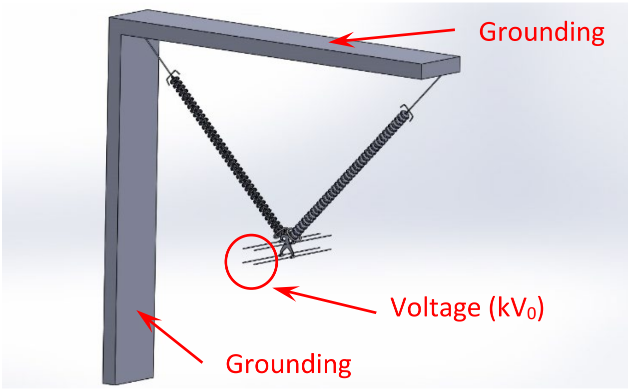

Fig. 17C: V-suspension set model with extension link, horizontal cross-arm, and vertical plane.

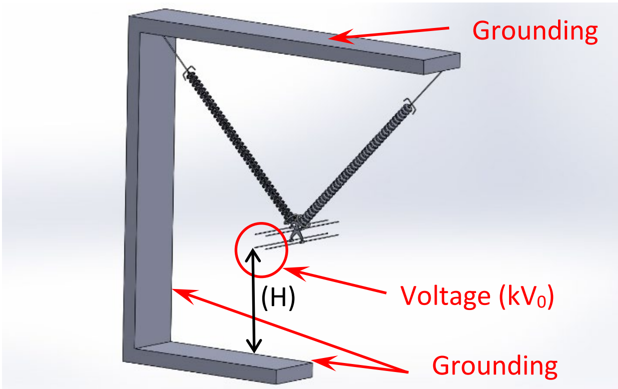

Fig. 17D: Complete model.

The voltage grading curves hereafter clearly showed the effect of the tower that lowers the voltage primarily at the ground end of the strings, along the 8 to 9 last (upper) units: The curve (in black) without any tower modeling exhibits the highest voltage, whereas the curves with complete tower modeling exhibit the lowest voltage. On the other end, it can be observed that the voltage grading is slightly increased at the live end when tower modeling is added.

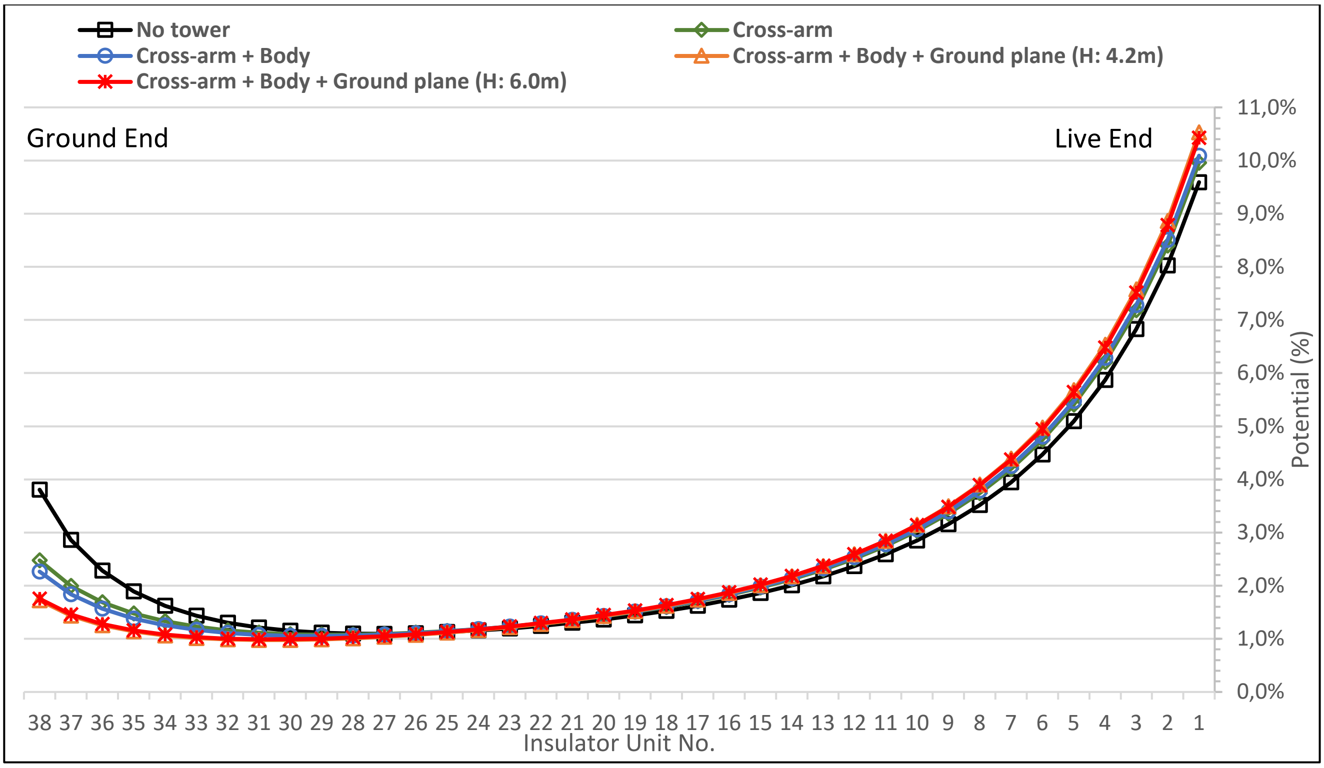

Fig. 18: FEA Computation of the voltage grading – Effect of the tower modeling

3.5 Example 6 – Effect of the Jumper Loops (Tension Sets)

As in real conditions they are oriented towards the ahead or back conductor spans of either side of the tower, simulations for tension insulator sets may be performed with only a horizontal plane representative of the tower cross-arm to which they are attached. However, the effect of the jumper loops connecting the sets on either side shall not be neglected.

In this study, a triple tension set with one arcing ring at the Live end was modeled with or without jumper loop.

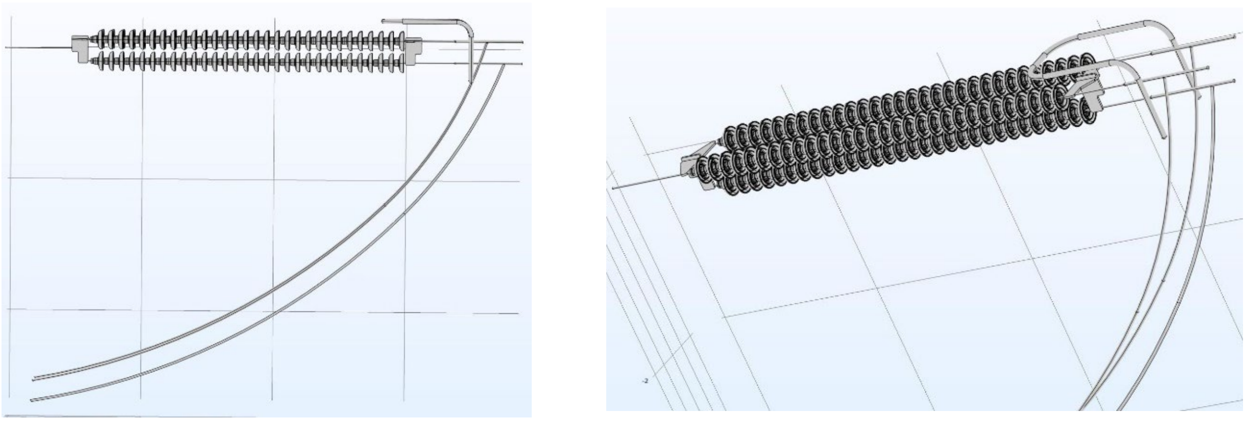

Fig. 19: Overall model of a triple tension set with jumper loop

The computation showed that the increase in the voltage across the insulator units at live end was reduced as the energized conductors of the jumper loop get closer to the strings. The computation confirmed again the beneficial effect of the arcing rings above the upper insulator strings compared to the lower one.

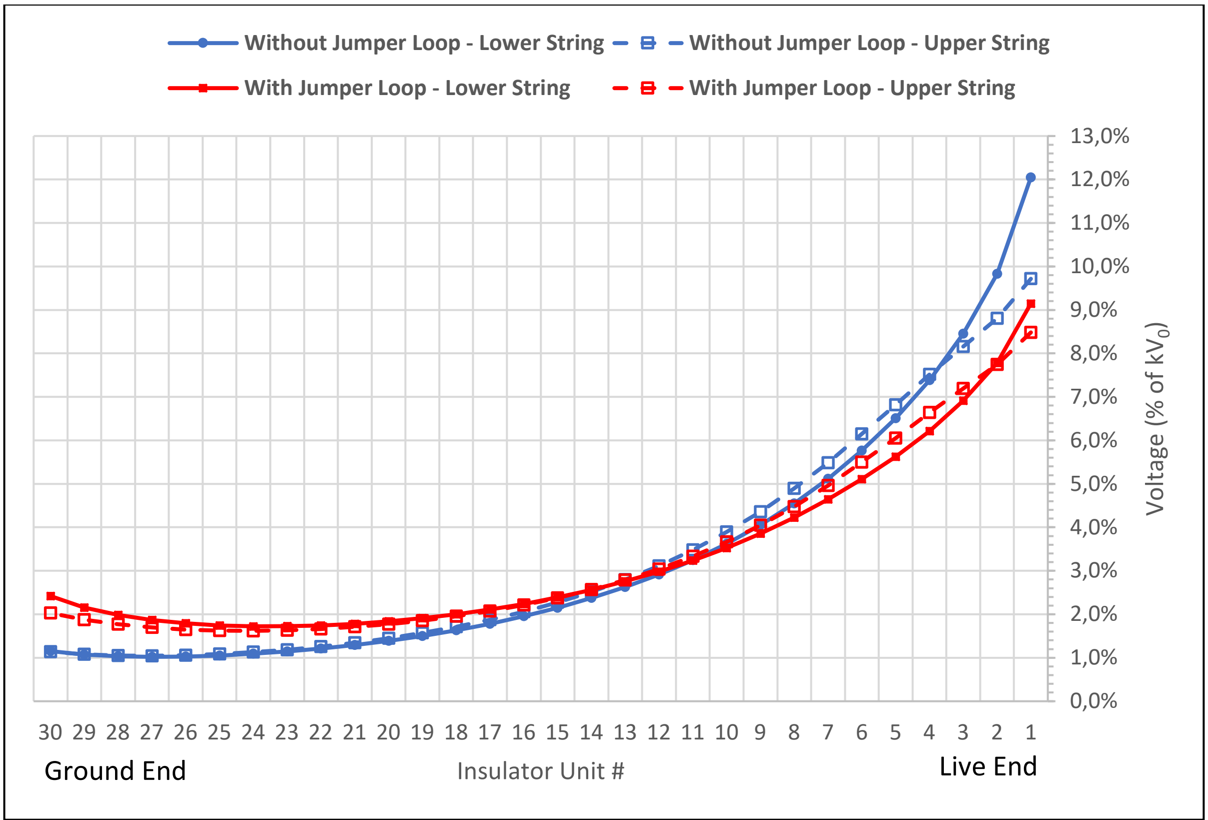

Fig. 20: FEA Computation of the voltage grading – Effect of the jumper conductor loop

4 What Not to Expect: FEA Limitations

These simulations were worked out on insulator unit in dry and clean condition; the pollution phenomena were not considered. RTV silicone coating on the toughened glass (or porcelain) shell surface was not considered since it does not significantly impact the E-field but primarily the leakage current whenever this pollution is present.

All these numerical simulations of electric field and voltage grading were based on the Maxwell's Equations of Electromagnetism; those do not take the pollution phenomena into consideration, primarily the dry band arcing under pollution.

In the current state of knowledge, no physical model or mathematical model, and no standard procedure have been established yet to simulate a polluted surface where the contaminant deposited can be more or less uniform in thickness, more or less evenly distributed over the surface, more or less conductive, more or less dry, unevenly wet… Moreover, the dynamic nature of dry band arcing can simply not be considered in a static or quasi-static simulation.

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[i] COMSOL Multiphysics. See www.comsol.com