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Voltage Gradient Study of HVDC Overhead Line Suspension Insulation

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A suspension composite insulator has been designed for the High Voltage Direct Current (HVDC) energisation of an overhead line supported by the L7 tower of Scottish and Southern Energy (SSE). It has been chosen to apply a pole to ground voltage of 216 kV for a triple symmetrical bipolar scheme. To verify the feasibility of the design, it has been necessary to study the possible corona effect and pollution accumulation areas on the insulator. Thus, with the use of COMSOL Multiphysics®, a Voltage Gradient investigation has been conducted along the object profile. To achieve this study, a comprehensive Flow Chart for HVDC Transmission Line Modelling is presented and it may serve as a reference to those approaching this Research field. The Flow Chart explains the strategies to simplify the model in order to solve it in a reasonable time without losing the desired accuracy of results. The geometrical simplifications of the tower core body and of the metallic cross arms are discussed.

The results suggest the corona effect would occur at the insulator ends, because the electric field is locally higher than the dielectric strength of air. As a consequence, the deployment of corona rings or alternative solutions are needed to alleviate the insulators present electric stress which would otherwise significantly reduce their lifetime. This conclusion demonstrates the need to verify the Voltage Gradient along a newly designed insulator surface.

Introduction

The electric power demand rise seen in the past century is going to persist in the coming decades, given the transforming automotive sector towards electric solutions and the electrification of residential heating. To allow such radical transition, the power transfer capability of the grid must be increased. One of the ways to do so is to utilise existing overhead transmission infrastructure to transfer direct voltage and current and increase power flow. Many **studies** have proved the potential to increase the line power transfer by a factor of two or more, according to environmental and climatic conditions. Only a **few projects have been realised (yellow notebook)** yet. However, some organisations are starting new business investigations about the topic to further deploy this solution [1], [2].

This paper focuses on the hypothetical utilisation of the SSE L7 tower. It describes in a brief way the HVDC selection and dimensioning of insulation, and in an extensive way how and under what simplifications its Voltage Gradient distribution has been calculated. The latter has been achieved by using cascade techniques to simplify the calculation, whenever this process would not compromise the accuracy of results.

The whole process will be schematically explained in the Methodology with a Flow Chart that can be applied for any other study of this kind. Then, the following techniques will be explained: simplification of the tower body, simplification of the tower metallic arms, exploitation of insulation axisymmetry. This comprehensive approach has not been utilised in previous works for a.c. energisation [3].

The Results section will justify the simplification choices that will ultimately lead to the study of the insulation Voltage Gradient. The identification of corona inception areas and pollution accumulation areas will be discussed. Depending on the results, the employment of corona rings will be assessed.

Methodology

The Method utilised in the paper is shown in the Flow Chart of Figure 1. It explains the logical sequence that can lead to the study of the Voltage Gradient of the insulator designed to withstand HVDC voltage in wet polluted conditions, starting from the 2D drawing of the SSE tower.

The Method is composed by two different Paths. The one listed with Latin characters on the left is self-sufficient, whereas the one listed with Greek characters on the right needs the information provided by the former.

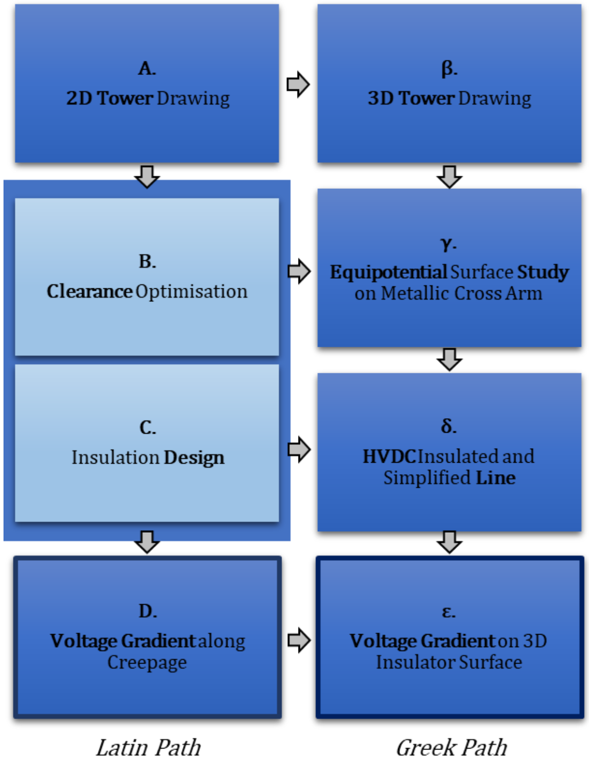

Figure 1. Complete Flow Chart for the realisation and simplification of the model.

The Latin Path. The 2D Tower Drawing leads to the determination of the HVDC insulation features and clearance between the High Voltage conductors and the live parts of the tower, which are grounded. Points B and C are mutually dependent and are explained schematically in Figure 2. Their extensive explanation has been previously conducted [4]. As a consequence of the determination of these points, which depend on the selected pole to ground voltage, the Voltage Distribution or Electric Field Magnitude can be calculated along the Creepage path of the insulator, using an axisymmetric model, which will save computational time with regards to a 3D model of the insulator.

The Greek Path. On the other hand, the 3D Tower Drawing can be realised by respecting the following rules. The first is that the tower core-body is constituted by multiple truncated square pyramids. The base of the i+1th pyramid and the truncated top of the ith pyramid is situated at each edge where the angle between two external supporting steel bars is different from 180° in the 2D Tower Drawing.

The metallic cross arms of the tower are square pyramids, but in the case of the L7 tower the upper and lower faces are not meshed by steel bars, which make the metallic cross arm an open Faraday Cage. This feature implies the need to study the intensity of the Equipotential Surface penetrating the metallic cross arm, which depends on the determined pole to ground voltage in points B and C and the metallic cross arm design. If the ratio between the largest Equipotential Surface voltage value and the pole to ground nominal DC voltage is considered to be too large, e.g. 5%, then the simplification of the metallic cross arm shall be avoided. This way, the Voltage Gradient calculation along the insulator will not be affected by the wrong assumption that the metallic cross arm behaves as an ideal Faraday Cage. This assumption will be generally valid for the tower core body instead. In fact, the L7 tower structure is completely meshed by steel bars, making it possible to be simplified as a full metallic object or a general object with a delimiting metallic surface. It is a well know fact that the potential of such body will be the same in every point, so meshing can be avoided.

The insulators can be added to the 3D drawing and finally the Voltage Gradient on the 3D Insulator Surface can be calculated. Again, the use of an integrated axisymmetric model of the insulator in the 3D model can be used, to try and speed up the computation.

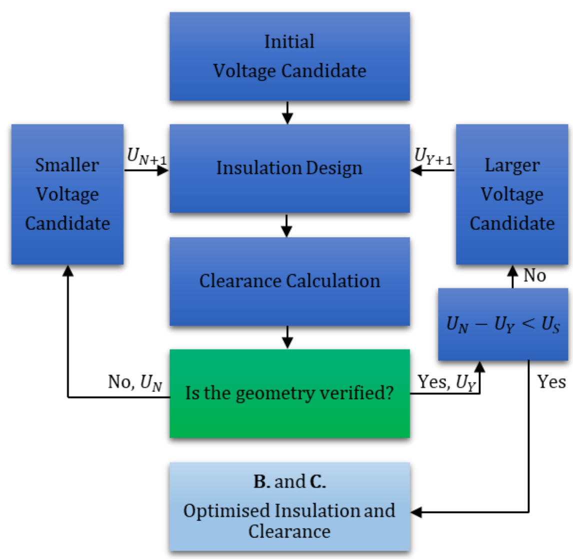

Figure 2. Secondary Flow Chart for the determination of points **B.** and **C.** of Figure 1.

Figure 2 Flow Chart is an iterative scheme aimed at determining the maximum voltage that can be applied between pole and ground of the triple bipolar scheme, while safely operating the line in wet polluted conditions and under switching surge disturbances. An initial voltage candidate is chosen and, after the insulation design is completed, the clearance distance is calculated to verify it fits in the tower geometry. If it does, a larger voltage level can be chosen and the process can be repeated. Contrarily, if it does not fit, a smaller voltage will be chosen and assessed. The process continues until the difference between two voltages with an opposite outcome is less than the nominal voltage of a converter switch. This way, the final selected voltage can be as accurate as the switch rating, indicated as U_S in Figure 2.

Modelling of the Line

To facilitate the reader to successfully implement the proposed Modelling Method and to explain the value of the strategies finalised to run the simulation faster, the following list shall be of interest.

AC/DC Module. The computation of points D, γ and ε is aimed at finding the solution of axisymmetric and 3D electrostatic problems. Thus, the AC/DC Module can be used by setting the chosen voltage at the surface of the conductors and by grounding the whole tower.

CAD Import Module. The drawings of points C, β and δ of the Method can be imported in the Model Builder with the CAD Import Module. The Insulation Design of point C can also be imported without the use of the Module, being a 2D drawing which can be revolved under the assumption of axisymmetry.

Mixed 3D and axisymmetries. The tower geometry is three-dimensional and the insulator geometry is axisymmetric. It is possible to represent both in the same Model by using the Work Plane tool in the Model Builder. The positioning and the rotation of the work plane must be set in accordance, in a way that the 360° rotation of the insulator profile occurs around its axis. 6 different work planes can be created, each one with its own rotation. Attention must be paid to the positioning of the insulators on the tower. After importing the 3D structure of the simplified tower, it is possible to run the simulation.

Mesh. It is of primary importance to assign the appropriate mesh element dimensions. In fact, the computational time of the simulation will greatly depend on the number of elements the mesh generates, being larger if the elements number is large. The consequence is that the mesh complexity must be contained. Generally, the elements can be coarser in the regions of low interest, such as the external Model boundary, where the electric field is imposed to be zero, and they should be finer on the areas of research interest. Thus, in this case, the mesh is finer on the insulators.

Results and Discussion

This Section will show the results according to the Complete Flow Chart of Figure 1. The presentation order will see first the Latin Path followed by the Greek Path.

·***Latin Path***

The 2D Tower Design of Figure 3 leads to the optimised Clearance of Figure 4 and the selection and dimensioning of the insulation in Figure 5.

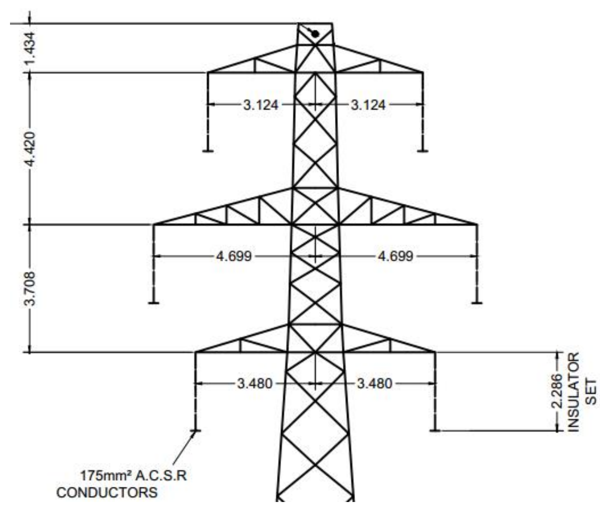

Figure 3. Point **A.**: SSE 2D Tower, initially utilised for HVAC transmission.

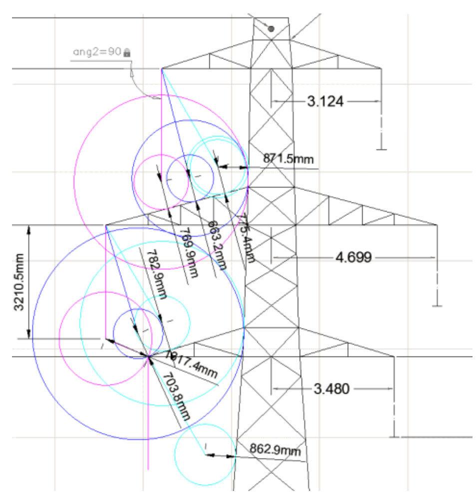

Figure 4. Point **B.**: Optimised Switching Impulse Clearance, calculated for different line expositions to wind, as explained in [4].

The optimised selected voltage is 216 kV. For more details on the motivation, the reader can refer to [4].

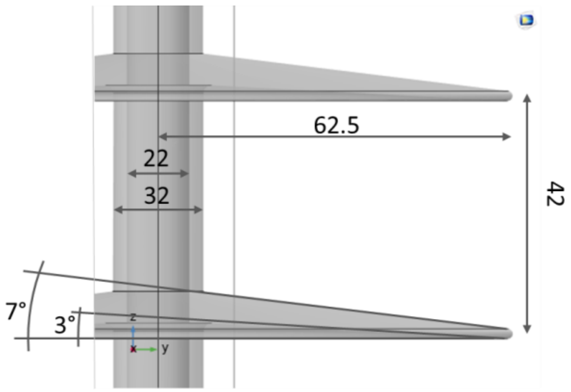

Figure 5. Point **C.**: Selected and Dimensioned Insulator, according to the Clearance, with detail on the sheds profile.

The numbers are expressed in millimetres (mm). The total length of the insulator, including the metal end fittings is 3210 mm. The insulator umbrella is made of silicone rubber with an inner glass fibre core.

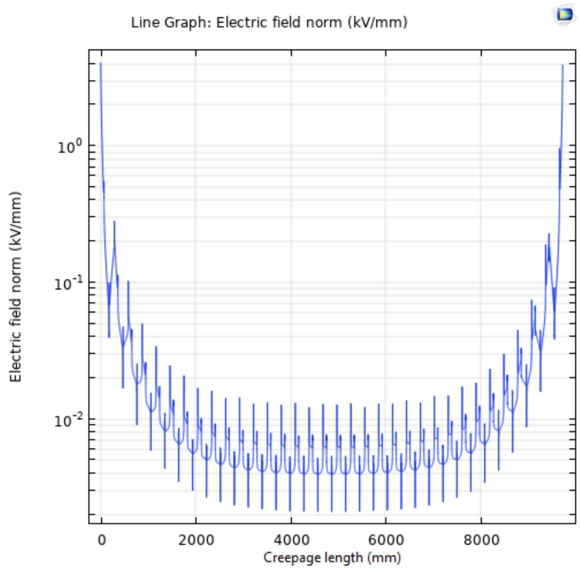

Figure 6. Point **D.**: Electric field magnitude along the creepage path of the insulator.

The electric field magnitude along the creepage path allows to recognise that the insulator ends are more prone to the corona inception, which indicates a higher risk of fast dielectric degradation. Moreover, the pollution accumulation is also stronger at the insulator ends, which, together with moisture, initiates partial discharge, responsible of dielectric degradation.

·***Greek Path***

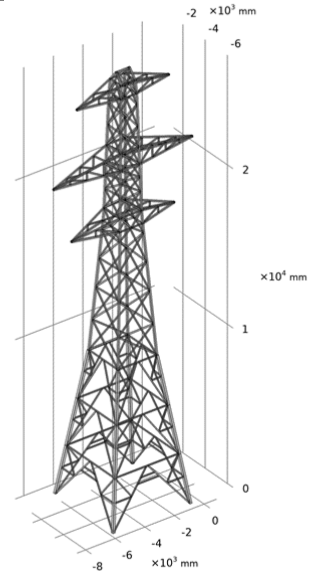

Figure 7. Point **β.**: 3D Tower Drawing.

Figure 7 shows how intricated the 3D Tower Design is. Thus, the authors suggest to directly simplify the central body of the tower. However, this simplification needs to be challenged when studying transients.

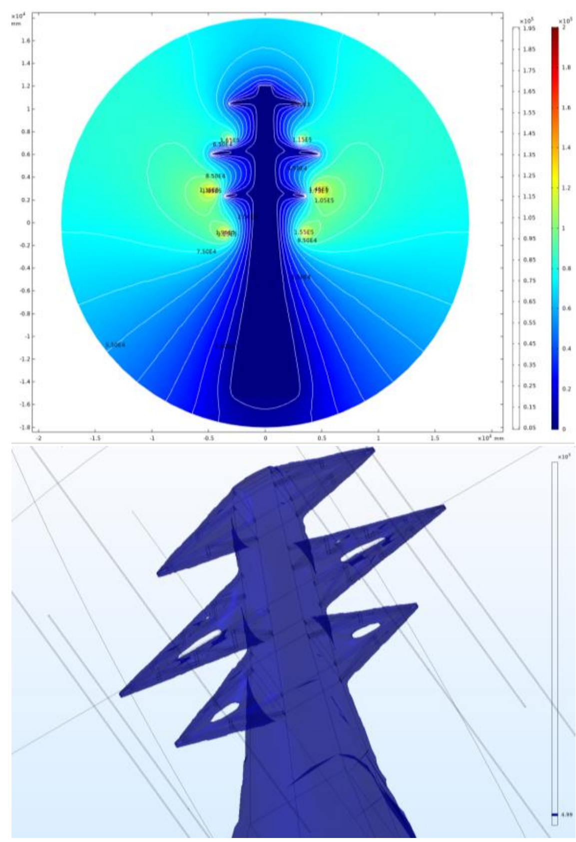

Figure 8. Point **γ.**: Study of the Equipotential Surfaces penetrating the metallic cross arms. Above, full frontal

tower. Below a 4.99 kV Equipotential Surface, penetrating the middle and lower metallic cross arms.

It is not necessary to represent the insulators as these would not greatly influence the results at the metallic cross arms. This is a key point, because doing otherwise may cause an excessive simulation time.

It is possible to observe in the lower sub-figure of Figure 8 that a 5 kV Equipotential Surface penetrates the middle and lower metallic cross arms. For brevity and clarity, that is the only surface shown. However, the 9 kV Equipotential Surface has been found to bend into the middle metallic cross arms.

The choice of not simplifying the metallic cross arms of the tower has therefore been justified.

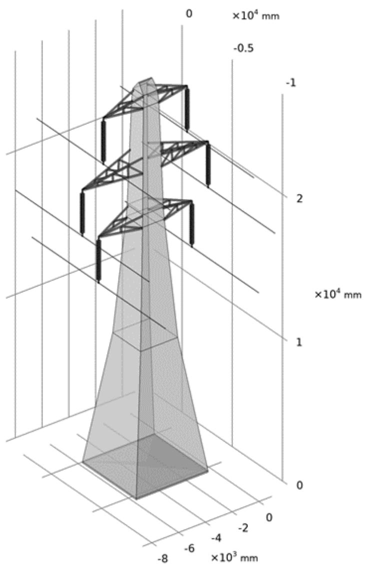

Figure 9. Point **δ.**: HVDC Simplified and Insulated Line energised with three bipolar schemes.

At this point, all the simplifications have been made. Depending on the computational power at disposal, it may be possible to simulate the whole line or a portion of it. In this paper, the most critical region of the tower has been studied, following the logic of caution. The most critical region is represented by the upper metallic cross arm, the insulator and the conductor. It is critical, because the distance between the 216 kV DC Voltage of the highest conductor and the grounded middle metallic cross arm, shown in Figure 10, is the minimum distance between the direct High Voltage and ground in the whole Model.

Figure 10 shows how the voltage is distributed along the insulation. It is possible to observe how the voltage gradient intensifies towards the High Voltage conductor.

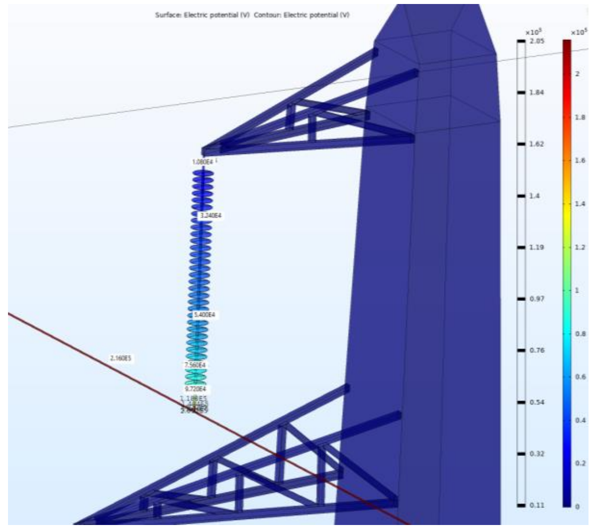

Figure 10. Point **ε.**: Voltage Distribution on 3D insulator surface.

Conclusions

By following the Flow Chart of Figure 1, it was possible to simplify the SSE L7 Tower Model for hypothetical HVDC transmission use. The trade-off between accuracy of results and computational speed has been optimised and the Voltage Gradient distribution along the insulator Creepage Length has been obtained. It is possible to conclude that the implementation of corona rings is needed for this newly designed insulator. Therefore, further studies are needed to assess the efficacy of such application. The simulation of insulation shall include the modelling of the wet-polluted layer.

This paper also opens the way to assess the feasibility of alternative insulation arrangements for this and other towers.

References

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