

## Electric Field Stress Calculation on High Voltage Insulator

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**Abstract:** A method is described for optimizing the field stress on HV insulators by modifying their profile, seeking a uniform distribution of the tangential field along the insulator surface. This results in an increase of the onset voltage for surface flashover and in a significant saving of the space of the HV installation. The optimization process was achieved by an algorithm developed for calculating the tangential field component and mathematical expressions of the profile to be corrected through an iterative procedure. The algorithm was based on a modified charge simulation technique to satisfy a better matching of the boundary conditions to the electrode and insulator surfaces involved in the HV installation. The algorithm is expanded to study the effect of contamination on the tangential field distribution. It is found that the higher the conductivity of the contamination layer, the higher is the field uniformity along the insulator surface.

**Keywords:** Field Stress, Contamination, Optimization, Insulators, Tangential Field

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### I. Introduction

HV insulators usually serve as a support/spacer of HV electrodes with respect to grounded frames (e.g. in gas-insulated systems) or the ground plane (in air). In practice, there are many applications where the HV insulators are surrounded by gaseous dielectrics and stressed between two electrodes depending on the arrangement. Flashover takes place along the insulator surface if the tangential field is high enough to sustain a discharge. To keep the tangential field below the limit required for a sustained discharge, the insulator length has to be a minimum value for a given voltage rating with a subsequent minimum cost of installation. Another efficient approach is to design the insulator with an optimized profile with a resulting shorter length, thus minimizing the space needed for installation.

To optimize a HV insulator, the distribution of the tangential field component along its surface should be uniform, thus increasing the onset voltage of surface flashover. This was achieved by correcting the profile of the insulator step by step. At any point on the insulator surface, the tangential field is derived from the potential difference between two test points in the vicinity of the point under consideration. If the tangential field exceeds the demanded value, either the potential difference is decreased, or the distance between the test points is increased.

Here, to optimize the HV insulator a Simulation is done through software named Finite Element Method Magnetics (FEMM). Where various models can be designed and tested for various parameters and the necessary changes can be made in the designed model in order to achieve the desired design. The software provides the platform to perform various trial and error approaches before concluding to the final results. Thus, benefiting the designers and manufacturers from actually building the setup which may require huge capital and funds for the same.

To study the effect of contamination on the insulator upon the tangential field, the simulation charges is replaced by complex charges. The contamination layer is simulated by a uniform surface resistivity along the insulator. The magnitudes of the simulation charges (real and imaginary components) is determined by a fore mentioned concept of error-function minimization. First, the algorithm is developed for calculating the tangential field is explained. Then the method of optimization is discussed, and the effect of contamination on the calculated tangential field distribution is investigated showing how the developed algorithm will accommodate this effect. Finally, the results obtained are discussed.

### II. Effect Of Contamination

To study the effect of contamination of the insulators upon the tangential field distribution, the algorithm developed is expanded to treat capacitive-resistive fields as well. The simulation charges were replaced by complex charges. The contamination layer was simulated by a uniform surface resistivity along the insulator.

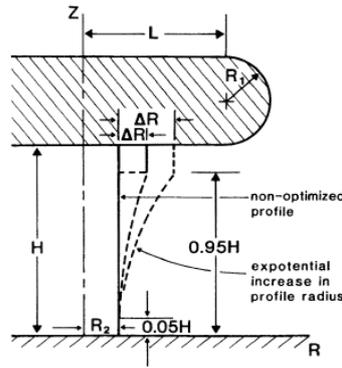


Fig. 1. Proposed approach for profile optimization.

The capacitive fields are not frequency dependent as long as  $V$  is the instantaneous value of the applied voltage. However, capacitive-resistive fields are field distribution along the insulator surface. For ac applied voltages, the capacitive and ohmic (due to the resistivity of the contamination layer) components will determine the tangential field distribution along the insulator surface. It has been realized [12] that the charge simulation technique is more accurate when compared with other techniques, e.g., finite-difference, finite-elements, Monte Carlo, and surface-charge simulation techniques frequency dependent.

It has been realized [12] that the charge simulation technique is more accurate when compared with other techniques, e.g., finite-difference, finite-elements, Monte Carlo, and surface-charge simulation techniques. formulate the error function with complex simulation charges, the following deviations  $\delta_{11}$ ,  $\delta_{12}$ , ...,  $\delta_{32}$  have to be defined.

$$\delta_{11} = [\phi_1(r, z)]_{\text{real}} - V$$

$$= [\phi_2(r, z)]_{\text{real}} - V$$

$$\delta_{12} = [\phi_1(r, z)]_{\text{imag}}$$

$$= [\phi_2(r, z)]_{\text{imag}}$$

$$\delta_{31} = \epsilon_r [E_{ri}(R_2, z)]_{\text{real}} - [E_{ra}(R_2, z)]_{\text{real}} - \sigma_{\text{real}}$$

$$\delta_{32} = \epsilon_r [E_{ri}(R_2, z)]_{\text{imag}} - [E_{ra}(R_2, z)]_{\text{imag}} - \sigma_{\text{imag}}$$

Then the error function expressed before by (11) takes the Form

### III. Results And Discussion

Conventional Charge Simulation Technique Versus the Proposed Modified Charge Simulation Technique The conventional charge simulation technique (CCST) has to limit the number of boundary points to be equal to the number of unknowns. For capacitive and capacitive-resistive fields, the matrix defining the set of equations describing the passive space has numerous zero terms. Subsequently, the matrix has a wide variation in its elements ranging from very high values to zero values. This is reflected in the "matrix condition" when solved by Gauss or Crout decomposition algorithms [4]. On the other hand, the set of equations involving the unknowns are formulated in modified charge simulation technique (MCST) to match the given boundary conditions to a large number of boundary points on the surface of the electrode and the insulator. Then the equations are reduced in number, through the error-function minimization, to be equal to that of the unknown. For both capacitive and capacitive-resistive fields, the matrix to be solved is not only free from zero terms but also has no wide variation in its elements as in CCST. The values of the unknown charges obtained in the CCST satisfy the boundary conditions in a satisfactory manner only with a careful choice of both the number of simulation charges and the coordinates of these charges. Therefore, the simulation accuracy depends strongly on the assumptions concerning the simulation charges in both number and coordinates [7]. These assumptions are usually made on the basis of experience which may differ from one investigator to another. As the geometry increases in complexity by involving more than one dielectric, the experience of the investigator may fail to achieve the boundary conditions with an acceptable accuracy. This explains why investigators [5] used their expertise to choose the coordinates for their simulation charges in a nonsystematic manner to achieve the

boundary conditions. For capacitive and capacitive-resistive fields the number of simulation charges was large but not stated explicitly [5]. However, other investigators [6] did not mention how they choose the coordinates of their simulation charges for CCST to analyze capacitive fields. They found that with an increase in the number of simulation charges (to increase the number of boundary points involved in the matrix formulation), the results vary and a critical number is reached where the computed results became acceptable. Increasing the number of simulation charges with CCST sometimes leads to bad conditioning of solutions instead of producing better accuracy for a single dielectric geometry [7]. This agrees with the findings observed by the present authors when they tried to apply CCST for the two-dielectric installation they investigated and present in Fig. 1.

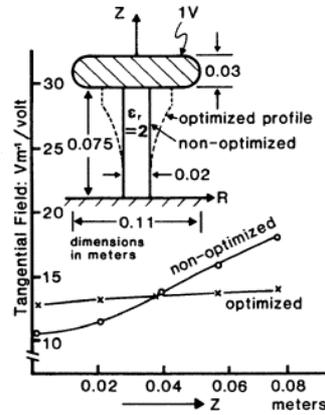


Fig. 2. Tangential-field distribution along profile for optimized and nonoptimized insulators.

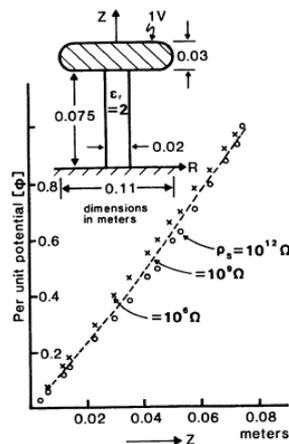


Fig. 3. Effect of resistivity of contamination layer on potential distribution along insulator.

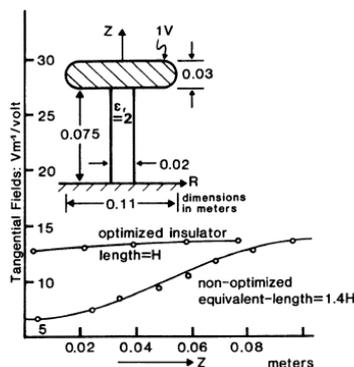


Fig. 4. Tangential-field distribution along optimized insulator and equivalent one.

In the MCST the coordinates of the simulation charges are chosen in a systematic way. The number of simulation charges ( $N_e + N_i + N_a$ ) is kept constant while the number of boundary points ( $n_e + 2n$ ) is increased in the range of two to five times ( $N_e + N_i + N_a$ ) depending on the passive space to be analyzed. Of course, the larger the number of boundary points, the better is the matching of the boundary conditions to the insulator and electrode surfaces. As a result, the MCST does not have a critical number of simulation charges whereas the

CCST does [6]. All of this is attributed to the improved condition of the matrix obtained from the error-function (minimization for capacitive fields and for capacitive-resistive fields). Accuracy of the MCST For capacitive fields the number of simulation charges  $N$ ,  $N_i$ , and  $N_o$  are chosen equal to 8, 12, and 12, respectively. However, the number of the boundary points on the electrode  $n_e$  and on the insulator surface  $n$  are chosen equal to 56 and 20, respectively. For capacitive-resistive fields the number of simulation charges  $N_e$ ,  $N_i$ , and  $N_a$  are chosen as 6, 9, and 9, respectively. However, the number of boundary points  $n_e$  and  $n$  are chosen equal to 54 and 18. Here, each charge involves two unknowns (real and imaginary components). While one boundary condition is to be satisfied over the electrode surface, two boundary conditions exist for the insulator surface. In other words, the number of equations written per point on the insulator surface is double that for a point on the electrode surface. This is why the number of boundary points  $n$  on the insulator surface is chosen smaller than the number of boundary points  $n_e$  on the electrode surface.

It is very satisfying to observe that the calculated potentials satisfy not only the boundary conditions on the insulator surface but also the boundary condition on the electrode where the deviation from the applied voltage  $V$  did not exceed one percent.

Of course, the accuracy of the potential calculation along the insulator surface reflects itself in the accuracy of the predicted values of the tangential field component.

### **3.1 Insulator Optimization**

Fig. 2 gives the tangential field distribution for the optimized and nonoptimized insulators. It is quite clear that the tangential field for the nonoptimized insulator is low near the ground plane and is high near the HV electrode. Such high field intensity may be the origin of flashover on the insulator surface. On the other hand, the field is almost uniform along the optimized insulator which makes the probability of flashover on the insulator lower for the same applied voltage. As shown in Fig. 3, the line integral of the tangential field along the insulator surface equals the applied voltage for both the optimized and nonoptimized profiles. This is also a measure of the accuracy of the proposed MCST.

### **3.2 Effect of Contamination**

Fig. 3 shows how the potential on insulator surface changes its distribution with increased conductivity of the contamination layer. The higher the conductivity (i.e., the lower the  $\rho_s$ ) of the contamination layer the higher is the field uniformity along the insulator surface and the higher the specific critical creepage distance. The latter is defined as the critical creepage distance per-unit voltage (cm/kV) at which flashover occurs on a contaminated insulator [7]. The field uniformity is attributed to the resistive field being more and more predominant with the increase of the contamination layer conductivity. At layer resistivities  $< 106 \text{ } \Omega/\text{square}$ , the resistive field becomes the predominating one, and the tangential field assumes a constant value along the insulator surface.

## **IV. Practical Considerations**

As discussed before, optimization of the insulators' profiles improves their electrical characteristics as the tangential field distribution becomes uniform along the insulator surface. It is worthwhile to discuss quantitatively the optimization process from an economical point of view as regards the cost of the insulating material and the space of installation. Does the optimized insulator require more volume in comparison with the nonoptimized one, and how much installation space does it save? To answer these questions, a comparative study is done between the optimized insulator and an equivalent nonoptimized one whose maximum tangential field is equal to the tangential field of the optimized insulator for the same voltage.

This is the criterion of comparison. Different lengths of nonoptimized insulators were attempted to search for the length which satisfies the criterion of comparison. It is found that a nonoptimized insulator of length equal to 1.4 times the length of the optimized insulator satisfies the criterion of comparison (Fig. 5). This means that the optimization process results in a 30-percent saving in the installation space. The relative volume of the optimized insulator is 50 versus 33 for the equivalent nonoptimized insulator. This indicates a 50-percent increase of the volume of the insulating material for the optimized insulator relative to the nonoptimized insulator.

On the other hand, it is not easy to compare quantitatively the mechanical stresses for the optimized and the equivalent nonoptimized insulators. For outdoor insulators momental stresses due to wind are the most important and depend upon the projected area and the length of the insulator as well as the wind speed over the projected area. An evaluation of the mechanical stresses is out of the scope of the present paper. However, brief comments can be made. The optimized insulator has a length equal to 70 percent of the equivalent one with a subsequent reduction in the momental stresses due to wind. Also, the relative projected area of the optimized

insulator is 21.6 versus 21.0 for the equivalent nonoptimized insulator. Therefore, the projected area of the optimized insulator is almost the same as that for the equivalent one. From these figures the optimized insulator appears to have better mechanical characteristics than the equivalent nonoptimized one. For HV insulators with corrugated surfaces the tangential field distribution along the nonoptimized profiles can be determined in a manner similar to cylindrical insulators. The coordinates of the simulation charges in the air and in the insulator have to follow the corrugated profile (in (3) and (4), the radius  $R_2$  at a given  $z$  coordinate is replaced by the radius  $r$  of the corrugated profile at the same  $z$  value). Of course, the  $n$  boundary points along the insulator surface have to be chosen along the corrugated profile.

To optimize the profile of HV insulators with corrugated surfaces, the mathematical expressions which describe the profile are not as simple as for cylindrical insulators. The iterative procedure may involve more parameters for modification to achieve an acceptable degree of field uniformity. However, the aforementioned comparison between the optimized and nonoptimized profiles as regards the saving installation space, the improvement of its mechanical characteristics, and the increase of the volume of the insulating material is still valid for insulators with corrugated surfaces.

## **V. Conclusion**

The conventional charge simulation technique is modified to satisfy better matching of the boundary conditions to the electrode and insulator surfaces involved in the investigated installation. The modified technique is characterized by systematic coordination of the simulation charges and by independence from a critical number of these charges as noticed with the conventional technique.

An approach is suggested to optimize the profile of HV insulators to have a uniform tangential-field distribution over their surfaces. The approach is simple in comparison with those reported in the literature. Insulator optimization results in an increase of the onset voltage for surface flashover, a significant saving of the space for the HV installation and an improvement of its mechanical characteristics on the expense of an increase in the volume of the insulating material. For contaminated insulators the higher the conductivity of the contamination layer, the larger is the degree of tangential-field uniformity over the surface.

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