OPTIMIZATION OF ELECTRIC FIELD STRESS 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 uniformityalong the insulator surface.

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

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 uponthetangential field distribution, the algorithm developed isexpanded to treat capacitive-resistive fields as well. Thesimulation charges were replaced by complex charges. Thecontamination layer was simulated by a uniform surfaceresistivity along the insulator.
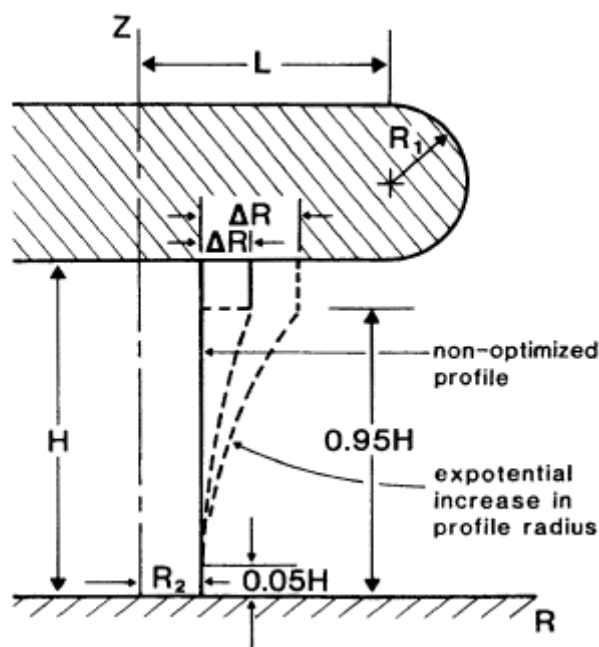

Fig. 1. Proposed approach for profile optimization.

The capacitive fieldsare 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 thecharge simulation technique ismore accurate when comparedwith other techniques, e.g., finite-difference, finite-elements,Monte Carlo, and surface-chargesimulation techniques. formulate the error function with complex simulation charges, the following deviations 611, 612,..., 632 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 theForm

III RESULTS AND DISCUSSION

Conventional Charge Simulation Technique Versus theProposedModified Charge Simulation TechniqueThe conventional chargesimulation technique (CCST) hasto limit the number of boundarypoints to be equal to thenumber of unknowns. For capacitive andcapacitive-resistivefields, the matrix defining the set ofequations describing thepassive space has numerous zero terms.Subsequently, thematrix has a wide variation in itselements ranging from veryhigh values to zero values. This isreflected in the "matrixcondition" when solved by Gauss or Croutdecompositionalgorithms [4]. On the other hand, the set ofequationsinvolving the unknowns are formulated in modifiedchargesimulation technique (MCST) to match the given boundaryconditions to a large number of boundary points on the surfaceof the electrode and the insulator. Then the equations arereduced in number, through the error-function minimization,tobe equal to that of the unknown. For both capacitive andcapacitive-resistive fields, the matrix to be solved is not onlyfree from zero terms but also has no wide variation in itselements as in CCST. The values of the unknown charges obtainedin the CCSTsatisfy the boundary conditions in a satisfactorymanner onlywith a careful choice of both the number ofsimulation chargesand the coordinates of these charges.Therefore, the simulationaccuracy depends strongly on theassumptions concerningthe simulation charges in both number andcoordinates [7].These assumptions are usually made on thebasis of experiencewhich may differ from one

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investigator toanother. As thegeometry increases in complexity by involvingmore than onedielectric, the experience of theinvestigator may fail toachieve the boundary conditions with anacceptable accuracy.This explains why investigators [5] usedtheir expertise tochoose the coordinates for their simulationcharges in anonsystematic manner to achieve the boundaryconditions. Forcapacitive and capacitive-resistive fields thenumber ofsimulation charges was large but not stated explicitly[5].However, other investigators [6] did not mention how theychoose the coordinates of their simulation charges for CCST toanalyze capacitive fields. They found that with an increase inthe number of simulation charges (to increase the number ofboundary points involved in the matrix formulation), theresultsvary and a critical number is reached where thecomputedresults became acceptable.Increasing the number of simulationcharges with CCSTsometimes leads to bad conditioning ofsolutions instead ofproducing better accuracy for a singledielectric geometry[7]. This agrees with the findings observedby the presentauthors when they tried to apply CCST for the two-dielectricinstallation they investigated and present in Fig. 1.
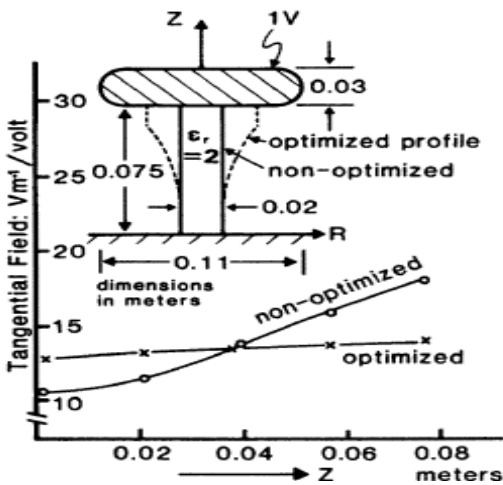

Fig. 2.Tangential-field distribution along profile for optimized and nonoptimized insulators
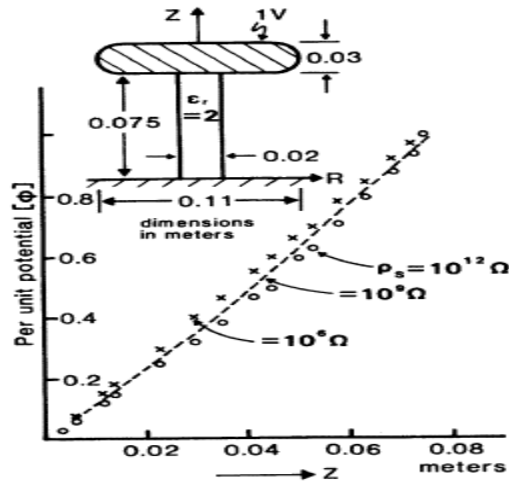

Fig. 3.Effect of resistivity of contamination layer on potential distributionalong insulator.
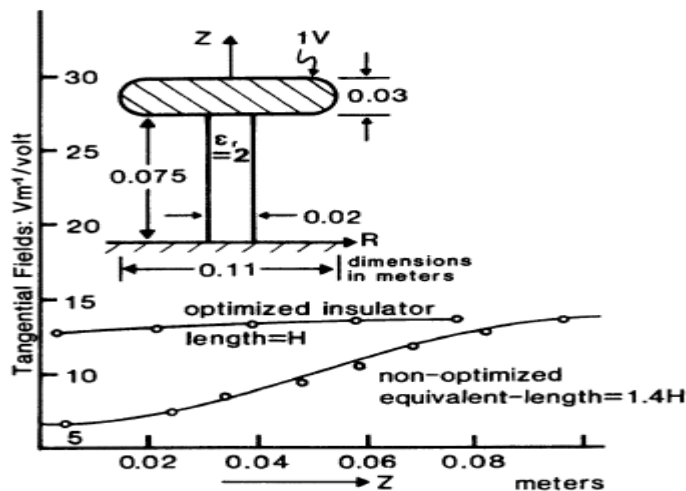

Fig. 4.Tangential-field distribution along optimized insulator and equivalentone

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In the MCST the coordinates of the simulation charges arechosen in a systematic way. Thenumber ofsimulation charges (Ne + Ni + Na) is kept constantwhile thenumber of boundary points (ne + 2n) is increased inthe range oftwo to five times (Ne + Ni + Na) depending onthe passive spaceto be analyzed. Of course, the larger thenumber of boundarypoints, the better is the matching of theboundary conditions tothe insulator and electrode surfaces. Asa result, the MCST doesnot have a critical number ofsimulation charges whereas the CCSTdoes [6]. All of this isattributed to the improved condition ofthe matrix obtainedfrom the error-function (minimizationfor capacitivefields andfor capacitive-resistive fields).Accuracy of the MCSTFor capacitive fields the number ofsimulation charges N,Ni, and No are chosen equal to 8, 12, and12, respectively.However, the number of the boundary points onthe electrodene and on the insulator surface n are chosen equalto 56 and 20,respectively.For capacitive-resistive fields thenumber of simulationcharges Ne, Ni, and Na are chosen as 6, 9,and 9, respectively.However, the number of boundary points neand n are chosenequal to 54 and 18. Here, each charge involvestwo unknowns(real and imaginary components).While one boundarycondition is to be satisfied over theelectrode surface, twoboundary conditions exist for theinsulator surface. In otherwords, the number of equationswritten per point on the insulatorsurface 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 ne 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 theinsulator 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 fieldintensity may be the origin of flashover on the insulatorsurface. 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 ps) 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 acontaminated 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 9/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' profilesimproves 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 R2 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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