ELECTRIC FIELD STRESS ANALYSIS FOR A COMPOSITE CONE TYPE SPACER DESIGNED FOR UNIFORM ELECTRIC FIELD DISTRIBUTION ON SPACER SURFACE IN THE PRESENCE OF A WIRE LIKE PARTICLE

D. Deepak Chowdary[1], J.Amarnath[2]

[1]Dr.L.Bullayya College of Engineering for Women, Visakhapatnam, A. P, India
[2]Jawaharlal Nehru Technological University, Hyderabad, Andhra Pradesh, India

ABSTRACT

The gas dielectric interface formed by solid insulating spacer and SF_6 gas represent the weakest point in Gas Insulated Systems (GIS). It is essential to determine the electric field distribution along the spacer surfaces and evaluate the degree of their reliability. A key aspect in the design and optimization process of insulating spacers is the precise simulation and geometric optimization of the electric field distribution on the dielectrics. Precise knowledge of the electric field distribution enables the electrical engineer to prevent possible flashovers in critical areas of the device being designed. The geometrical shape of the spacers has a significant influence on the resulting electrostatic field. Breakdown strength is severely affected by the presence of conducting particles in a GIS as these conducting particles will be resulting in enhanced field stress in the vicinity of the particle which may cause partial discharges and eventually result in breakdown of the system. Knowledge of electric field stress distribution along the surface of the spacer in the presence of a particle in the vicinity of the surface of the spacer will be helpful in understanding the insulation integrity of a GIS. In this paper a composite cone type spacer is designed geometrically to obtain uniform electric field stress along the surface of the spacer. A hemispherical capped wire like particle is considered and the electric field stress distribution along the surface of the spacer is computed in the presence of particle near to the surface of the spacer The Finite Element Method, an efficient technique for solving field problems, is employed to compute the electric field.

KEYWORDS: *Composite Spacer, Gas Insulated System, Finite Element Method*

I. INTRODUCTION

The breakdown of SF_6 gas insulation is adversely affected by the presence of insulator surfaces, unless special design precautions are taken [1].Gas Insulated systems require solid insulating materials to provide mechanical support for conductors. . For the enhancement of insulation reliability and compact design in gas insulated power equipment the solid insulators play crucial role of electrical insulation [2]. The study of electric field distribution in and around the supporting spacers has been of considerable interest for the design engineer for designing the equipment operating at high voltage levels [3,4]. Several troubles and system outages have been reported all over the world due to spacer's failures. Normally, pure SF_6 or SF_6/N_2 mixtures at high pressures are used to insulate the system [5,6]. The presence of spacers, results in complex-dielectric field distribution. It often intensifies the electric field particularly on the spacer's surface. The insulation ability of SF_6 is highly sensitive to the maximum electric field, and furthermore the insulation strength along a spacer's surface is usually lower than that in the gas space [7]. So the spacers used in GIS should be precisely designed to realize more or less uniform field distribution along their surfaces. Effort is to be made to decrease the electric field value as low as possible keeping in mind the optimum leakage path. Spacer's profile is considered the main variable, which controls the field distribution and hence field uniformity can be achieved by adopting the appropriate profile [6,8-9].

Practical gas insulated systems suffer from contamination by metallic particles. These can be introduced during assembly or are produced during operation as a result of vibrations, abrasion of components, etc. It is generally accepted that conducting particles with dimensions < 0.5 mm, do not cause a large reduction in the breakdown strength of gas insulated systems [10,11]. Long metallic particles, however, cause a substantial impairment of the maximum obtainable performance of gaseous insulation because they can migrate to critical regions [12-16]. Consider, for example, a horizontal coaxial conductor arrangement. A particle lying on the inner surface of the outer conductor will obtain a charge, which is proportional to the local field. Thus, the particle experiences an electrostatic force. At sufficiently high applied voltage, the particle will lift off and begin to move in the gas space between the conductors. At a sufficiently HV, a particle is able to cross the gap between the conductors and can initiate breakdown. Experimental and theoretical studies have shown that particle initiated breakdown is a two-stage process [15,16]. Under appropriate voltage conditions, local breakdown occurs between the centre conductor and a particle moving very close to this conductor. This local breakdown may continue in the rest of the gap between particle and outer electrode. It has been established that for a certain electrode arrangement, the free moving particle-initiated breakdown voltage is slightly lower than the breakdown voltage resulting from a particle stationary at a short distance from the surface of the high field electrode, and that this latter voltage is lower than the voltage associated with a particle fixed onto the surface of the high field electrode, at SF6 gas pressures < 0.1MPa [15].

During the movement of a particle in a horizontal coaxial conductor system, a horizontal velocity component is generated due to the irregular shape of the particle and/or electrode surface roughness. As a result, metallic particles will reach vertical insulator surfaces. The combination of metallic particle contamination and a solid insulator has proven to be the most crucial dielectric design consideration; however, only a few studies have been made to determine the effect of this combination on the dielectric strength of compressed SF_6 gas insulation [17-21].

The paper is organized as, section two explains the Finite Element Method(FEM) as applicable to the problem under consideration mathematically. In section three, a composite cone spacer is designed geometrically. In section four, a hemi spherically capped wire like particle is modelled. Section five presents electric field stress analysis on the surface of the spacer in the presence of wire like particle .

II. ELECTRIC FIELD COMPUTATION TECHNIQUE

To the date most of the research work related to electric field computation have been done using Charge Simulation Method(CSM). Acceptable results were obtained by this method. However, the choice of the number and charges types; point, ring and line charges need tedious trial and error methodology which is time consuming. FEM one of the efficient technique for solving field problems is used to determine the electric field distribution on the spacer's surface. FEM concerns itself with minimization of the energy within the whole field region of interest, whether the field is electric or magnetic, of Laplacian or Poisson type, by dividing the region into triangular elements for two dimensional problems or tetrahedrons for three dimensional problems [22]. Under steady state the electrostatic field within anisotropic dielectric material, assuming a Cartesian coordinate system, and Laplacian field, the electrical energy W stored within the whole volume U of the region considered is:

$$W = \frac{1}{2}\int_U \varepsilon |\mathrm{grad}V|^2\, dU \qquad (1)$$

$$W = \frac{1}{2}\iiint_U \left[\varepsilon_x \left\{\frac{\partial V_x}{\partial x}\right\}^2 + \varepsilon_y \left\{\frac{\partial V_y}{\partial y}\right\}^2 + \varepsilon_z \left\{\frac{\partial V_z}{\partial z}\right\}^2\right] dxdydz \qquad (2)$$

Furthermore, for GIS arrangement, when we consider the field behaviour at minute level the problem can be treated as two dimensional (2D) [23]. The total stored energy within this area-limited system is now given according to:

$$\frac{W}{\varphi} = \frac{1}{2} * \varepsilon \iint \left[\left\{\frac{\partial V_x}{\partial x}\right\}^2 + \left\{\frac{\partial V_y}{\partial y}\right\}^2\right] dxdy \qquad (3)$$

Where (W/φ) is thus an energy density per elementary area dA. Before applying any minimization criteria based upon the above equation, appropriate assumptions about the potential distribution V(x, y, z) must be made. It should be emphasized that this function is continuous and a finite number of derivatives may exist. As it will be impossible to find a continuous function for the whole area A, an adequate discretization must be made. So all the area under consideration is subdivided into triangular elements hence:

$$\frac{W}{\varphi} = \frac{1}{2} * \varepsilon * \sum_{i=1}^{n} \left[\left\{ \frac{\partial V_x}{\partial x} \right\}^2 + \left\{ \frac{\partial V_y}{\partial y} \right\}^2 \right] * A_i \qquad (4)$$

Where n is the total number of elements and Ai is the area of the i^{th} triangle element. So the formulation regarding the minimization of the energy within the complete system may be written as

$$\frac{\partial X}{\partial\{V(x,y)\}} = 0 \,; \text{Where} \;\; X = \frac{W}{\varphi} \qquad (5)$$

The result is an approximation for the electrostatic potential for the nodes at which the unknown potentials are to be computed. Within each element the electric field strength is considered to be constant and the electric field strength is calculated as

$$\vec{E} = -\vec{\imath}\frac{\partial V(x,y)}{\partial x} - \vec{\jmath}\frac{\partial V(x,y)}{\partial y} \qquad (6)$$

III. DESIGN OF A COMPOSITE CONE SHAPED SPACER

Gas-dielectric interface which is treated to be a weakest point in Gas Insulated System is a critical aspect of design. Electrostatic-field optimization of the profile of the gas-dielectric interface was studied as a means of improving the dielectric performance of epoxy spacers. Also the electric field at the junctions formed by the spacer-SF_6 Gas- conductor(enclosure) known as triple junctions also play a critical role in the design of spacers in Gas insulated systems. Particularly the triple junction formed at the cathode end junction is considered to be the point where the free electrons are emitted and if the electric field is high at these junctions these electrons may result in partial discharges which may eventually result in the breakdown of the Gas Insulated System. A composite cone shaped spacer was modeled which combines the advantage of the long leakage distance of a cone shaped profile with that of the quasi-uniform field distribution of a disc-shaped profile. The optimization procedure is based on controlling the field distribution by shaping the spacer profile and is dependent on geometry parameters at the spacer surface. The angles suspended by the spacers with that of electrodes is also taken into consideration for the design of the spacer.

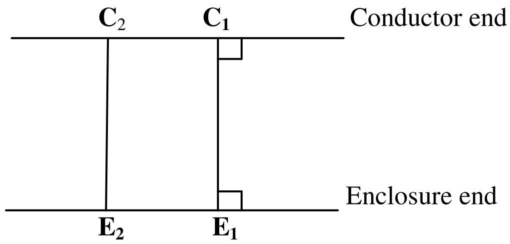

Figure 1. Disc Shaped Spacer-Type A, with the surface of Spacer perpendicular to the surface of the conductor.

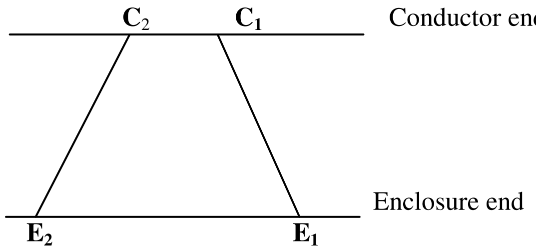

Figure 2. Disc Shaped Spacer-Type B, with the surface of Spacer making acute angle with the surface of conductor.

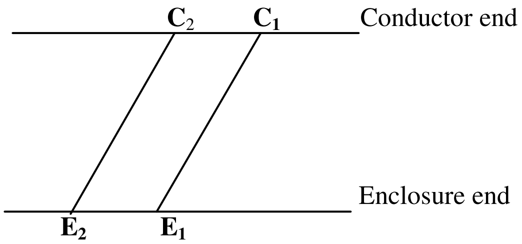

Figure 3. Cone type Spacer

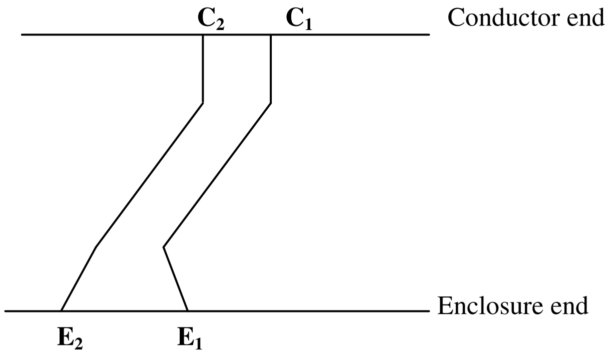

Figure 4. Crude Composite Cone Shaped spacer

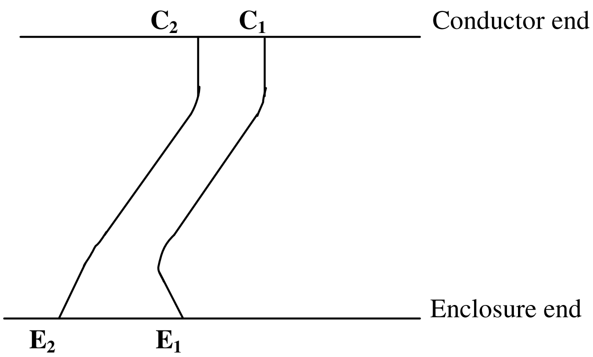

Figure 5. Composite Cone type spacer with smooth profile

For the disc spacer of Type-A shown in Figure 1, since the spacer surface is right angular(at Conductor end junctions,C_1 and C_2, Enclosure end junctions E_1 and E_2) with respect to the surface of the conductor and enclosure the field distribution along the surface of the spacer is given by E=V/d hence the field will be uniform however it has got a disadvantage of short leakage distance. For the disc spacer of Type-B shown in Figure 2, even though the leakage distance is increased compared to the spacer model shown in Fig. 1, the Cathode end junctions formed at C_1 and C_2 the angle subtended by the spacer will be less than 90^0 the field may reach to a high value. For the cone type spacer shown in Fig. 3 provides the longest leakage distance but the electric field distribution may not be uniform. Combining the advantages of spacer models shown in Figure 1 (uniform electric field), Figure 2 (taking the advantage of obtuse angles(>90^0) at E_1 and E_2 which will result in less electric field at the these junctions) and Figure 3(long leakage distance) a composite shape spacer is designed. The sharp edges of the crude composite spacer shown in Figure 4 may result in high stresses and therefore the spacer shape control is done to obtain uniform Electric field distribution along the surface of the spacer as similar to the figure shown in Figure 5.

3.1. Composite Cone Type Spacer

3.1.1. Spacer Profile

For geometry the difference between the radii of outer enclosure and inner conductor is taken as, r_o(outer enclosure radius)-r_i(Inner conductor radius) is equal to 100mm. A 1Volt is applied to anode while the cathode is maintained at grounded potential. It was assumed that no surface charge is accumulated on convex and concave sides of spacer. Figure 6 shows the initial shape of the spacer and importance regarding field optimization is given to the concave side of spacer as the junction formed by dielectric-SF_6-Electrode at cathode end is more vulnerable to flashovers. The optimized spacer profile is given in Figure 7. Electric field stress along the concave side of spacer is given in Figure 8 and electric field stress for optimized spacer profile is obtained for r=28mm as given in Figure 9.

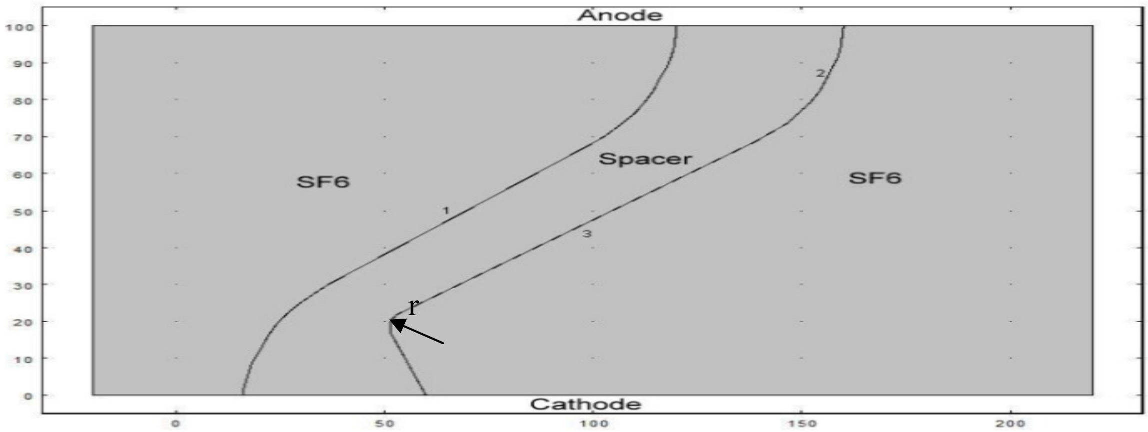

Figure 6: Initial Spacer Profile

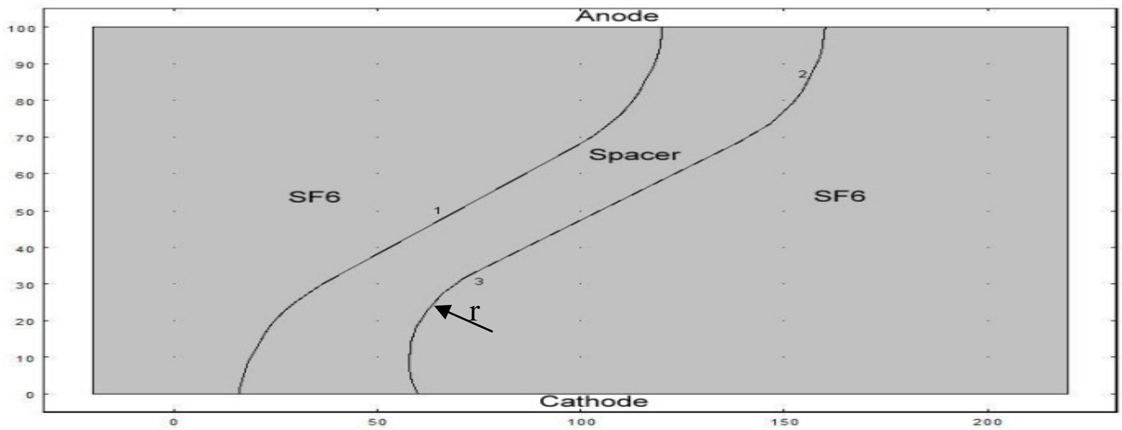

Figure 7: Optimized Spacer Profile

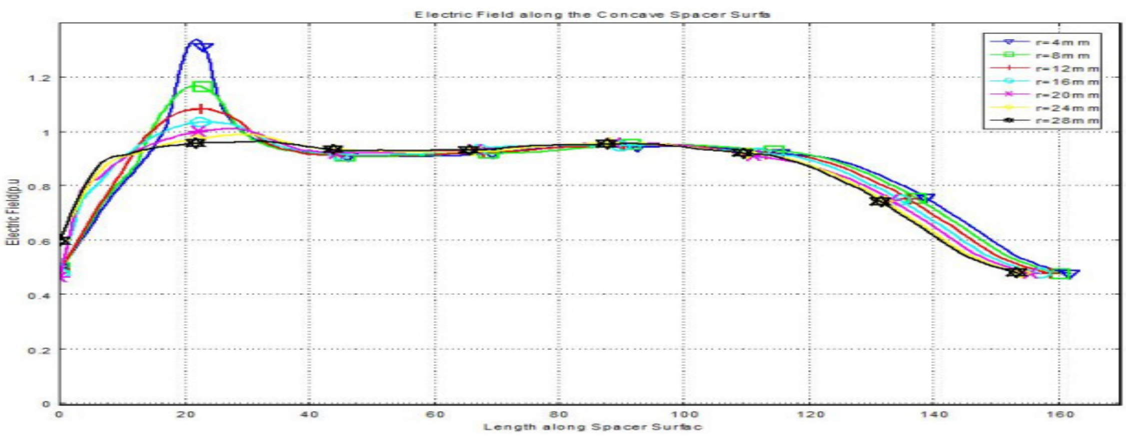

Figure 8: Electric Field Stress along the concave spacer surface for variable ‘r’

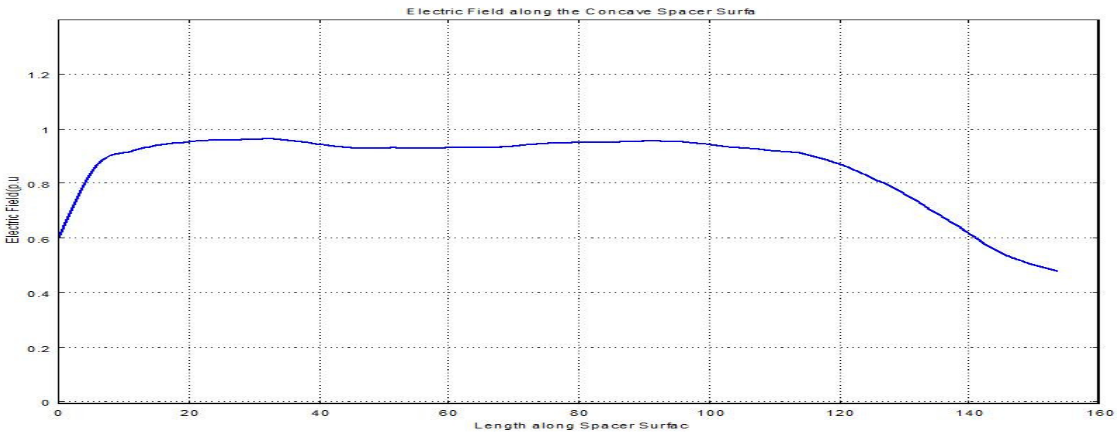

Figure 9: Optimum Electric Field Stress along the concave spacer surface for r=28mm

IV. MODELLING OF WIRE LIKE PARTICLE

For assessing the dielectric performance of spacer in the presence of particle contamination in gas insulated system a hemi spherically capped wire like particle is modelled with length l=10mm and hemispherical cap radius of 1mm as shown in Figure 10. This particle is considered to be present initially on the enclosure in vertical position.

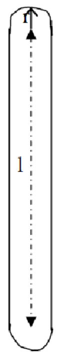

Figure 10: Wire like particle with length l and hemispherical tip radius of r.

V. ELECTRIC FIELD STRESS ANALYSIS IN THE PRESENCE OF WIRE LIKE PARTICLE

Initially a wire particle is considered to be resting on the surface of the enclosure in vertical position as shown in Figure 11. Different positions of the particle are considered under the assumption that the particle is moving vertically upwards towards the spacer. Under this assumption the electric field stress distribution along the surface of the spacer is computed. Figure 12 shows the particle final position near the surface of the spacer distanced at 0.5mm from its tip and Figure 13 its close up position. Figure 14 shows the electric field distribution along the surface of the spacer for different positions of the particle. From the graph shown in Figure 10 it can be observed that as the proximity of the particle with respect to spacer surface reduces the field along the spacer surface increases and for a particle distanced at 0.5mm from the tip of the particle the electric field approaches nearly to 4.5p.u.

Figure 15 shows different positions of the wire particle along the surface of the spacer. Figure 16 shows the electric field distributions for the positions mentioned in Figure 15. From the graph shown in Figure 16 it can be observed that when the particle is positioned with its hemi spherical tip near to spacer surface it will result in high field stress as the electric flux lines will be converging at these rounded surface. But when the particle surface is parallel to spacer surface it will result in low electric field stress.

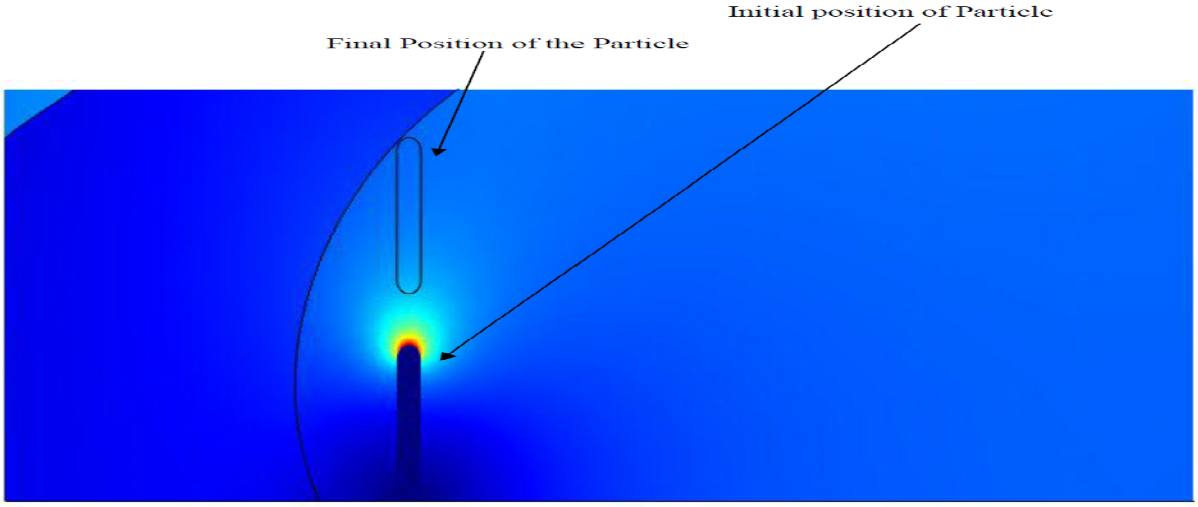

Figure 11: A wire like particle resting on the enclosure

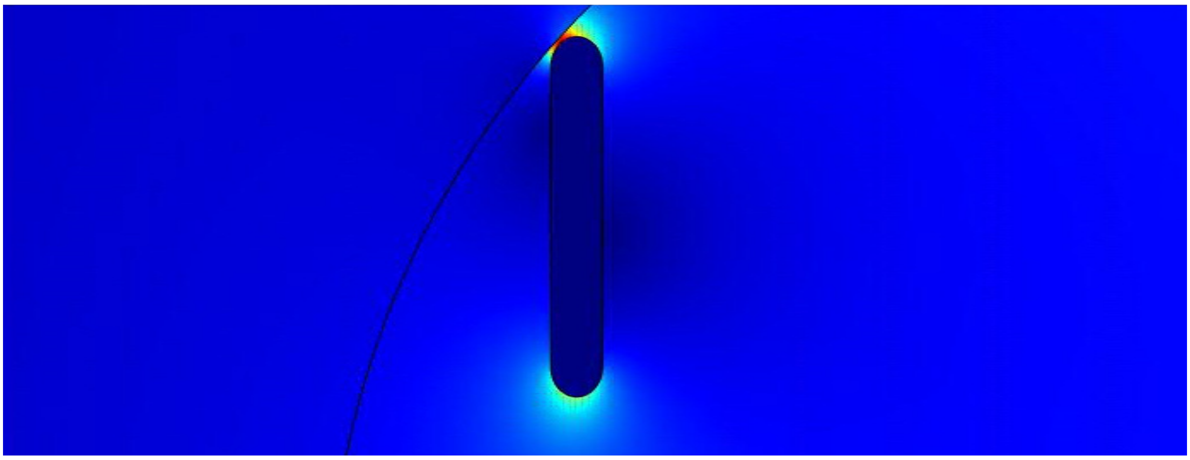

Figure 12: A wire like particle positioned at 0.5mm distance from the surface of the spacer

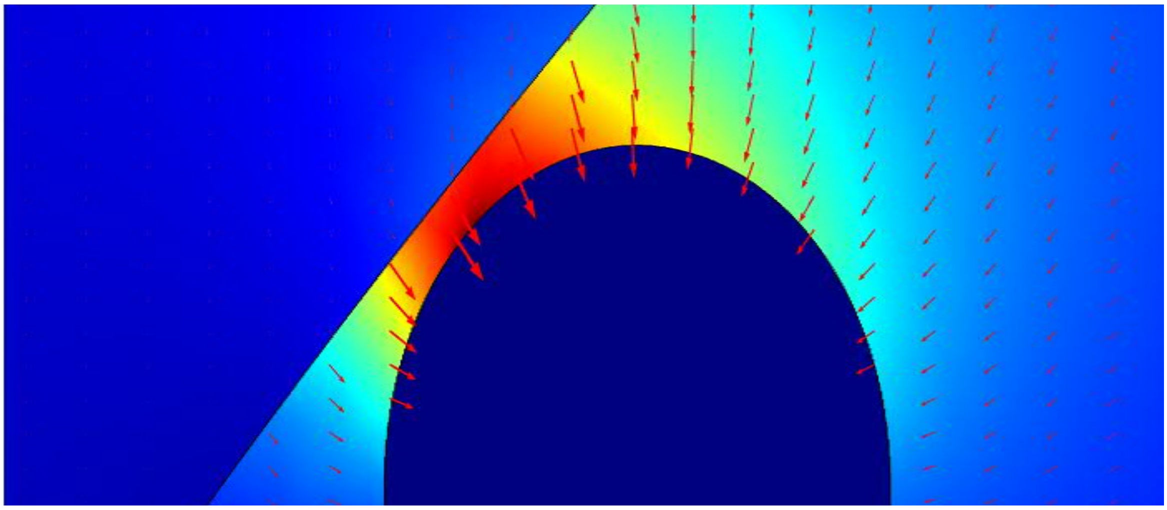

Figure 13: A wire like particle near to spacer surface a close up view

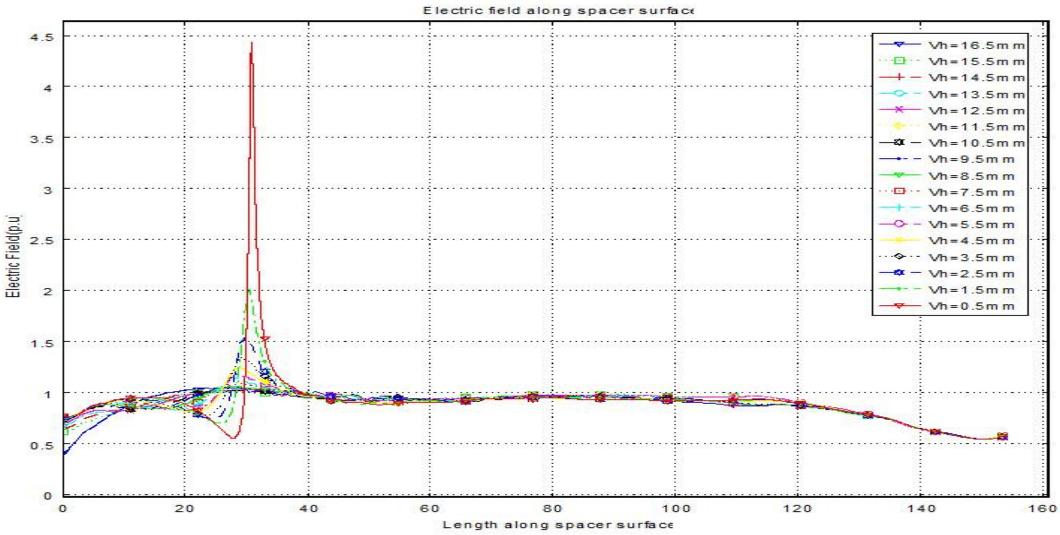

Figure 14: Enhancement of Electric field along the surface of the spacer during vertical motion of the particle

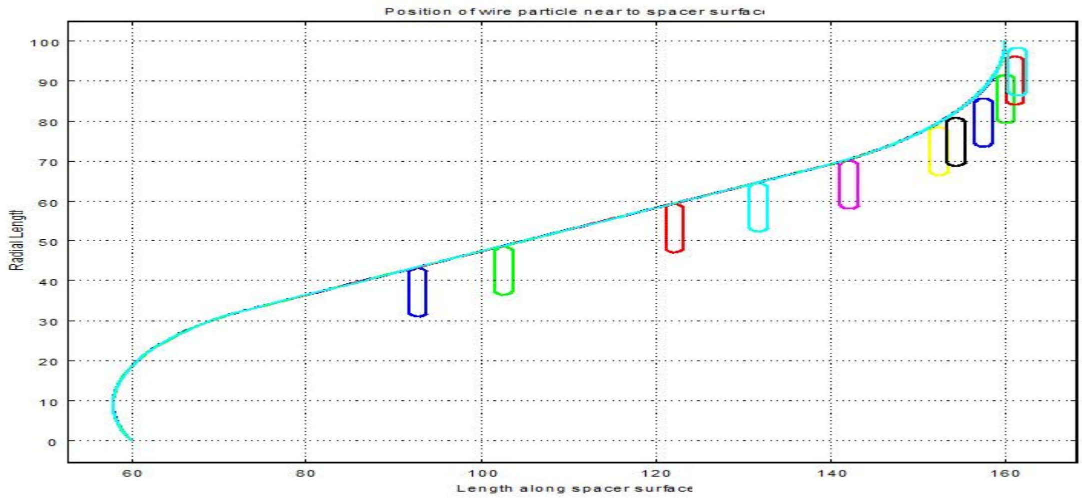

Figure 15: A wire like particle positioned at various points along the length of spacer surface

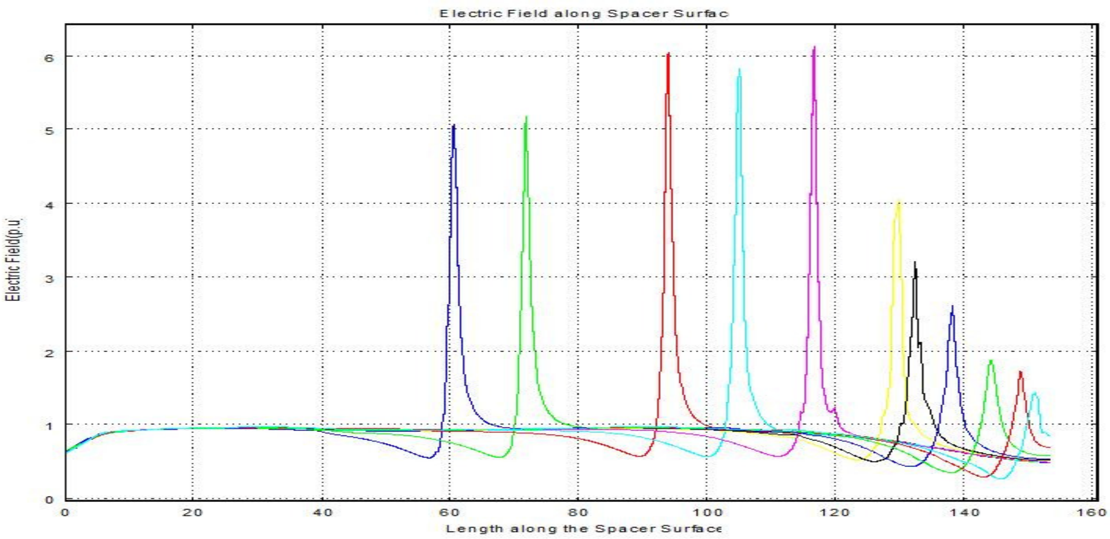

Figure 16. Electric Field stress distribution for a wire like particle positioned at various points along the length of spacer surface shown in Figure 15

VI. CONCLUSIONS

Precise simulation and geometric optimization of the electric field distribution on dielectrics is a key aspect in the design and optimization process of high voltage apparatus. Precise knowledge of the electric field distribution enables the electrical engineer to prevent possible flashovers in critical areas of the device being designed. The geometrical shape of the electrodes and dielectrics shows a significant influence on the resulting electrostatic field distribution. When designing and optimizing high voltage components it is very important to know the electric field distribution on the electrodes and dielectrics and in particular in the presence of contamination. At the starting of this paper, FEM, a numerical method used for computing electric fields is explained mathematically. Then a composite cone type spacer is designed geometrically to obtain uniform electric field along the concave side of spacer. Later a wire like particle is modeled and is considered to be present on the enclosure in vertical position. For the spacer designed for uniform stress field distribution, the stress analysis is carried on for different positions of the particle. First the electric field stress along the surface of the spacer is computed under the assumption that the particle is moving vertically upwards towards the spacer. From the computed field stress results it was observed that if the particle hemi spherical tip is near to the spacer surface it will result in high field stress. Then the particle is considered to be present at different positions along the surface of the spacer with its tip traversing nearby to the spacer surface. From the results it was observed that the positioning of the particle tip plays a important role in the enhancement of field stress distribution along the spacer surface and if the particle's flat surface is parallel to spacer surface the magnitude of field stress enhancement will be low.

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Authors

Deepak Chowdary Duvvada was born in Srikakulam, Andhra Pradesh, India in 1978.He obtained his bachelor of Engineering degree from GITAM college of Engineering, Visakhapatnam, Andhra Pradesh, India in the year 2000 and Master of Technology degree from JNT University, Hyderabad, Andhra Pradesh, India in year 2007. He is presently working as Associate Professor in the Department of Electrical Engineering, Dr. L. Bullayya College of Engineering for Women, Visakhapatnam, India. His research areas include Gas Insulated Substations, High Voltage Engineering and Custom power devices.

Amarnath Jinka graduated from Osmania University in the year 1982, M.E from Andhra University in the year 1984 and Ph.D from J.N.T. University, Hyderabad in the year 2001. He is presently Professor in the Department of Electrical and Electronics Engineering, JNTU College of Engineering, Hyderabad, India. He presented more than 60 research papers in various national and international conferences and journals. His research areas include Gas Insulated Substations, High Voltage Engineering, Power Systems and Electrical Drives.