The Impact of Cavity Size on Electric Field Distribution and PD Inception Voltage in Epoxy-resin Insulation

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***Abstract*— Cavities in insulation systems of active high voltage (HV) equipment affect their performance, reliability and useful life periods. Cavities serves as flash points for enhanced field activity leading to ageing from partial discharge (PD) events and subsequent breakdown of the insulation material. In this paper, the impact of cavity diameter on the electric field distribution as well as PD inception voltage is investigated in an Epoxy-resin insulation sample. A 3D adequate model of the sample with a spherical cavity was created and simulated in COMSOL for different cavity sizes and applied voltage stresses respectively. The simulation results indicate that the both field distribution and the PD inception voltages are strongly influenced by cavity size as well as the applied voltage magnitude. The electric field intensity was observed to be higher in cavities with smaller diameter relative to the insulation bulk, while the inception voltage decreases with increase in the cavity diameter and vice-versa.**

Keywords— Electric Field, COMSOL Multi-physics, Finite Element Analysis, Inception Voltage, Epoxy-resin Insulation

I. INTRODUCTION

Insulation is a critical components of any high voltage (HV) equipment. Its quality goes a long way in determining the efficiency and reliability of the apparatus in service. Insulation breakdown may lead to local disturbance such as as equipment malfunction, and subsequent failure. Thus, insulation condition monitoring is extremely important for healthy operation of the HV plants [1] and [2]

The emergence of defects such as cavities inside the insulation bulk of a HV plants enhances the electric field magnitudes, a critical phenomenon capable of initiating degradation within the equipment's insulation system. Depending on the size, location and geometry of such defects and consequent field values, partial discharge (PD) may occur [3]. Thus, measurement and analysis of the field distribution and how it is affected by the form of stressing quantity assists in monitoring the events of PD HV electrical installations [3].

Field modeling studies in several HV insulation systems with single and multiple defects have been widely reported in literature [4], [5], [6] and [7]. However, simulation studies relating to PD inception field in cavities are inadequate. The benefit of simulating PD inception field in a cavity is to enhance the understanding of one of the two major conditions for igniting a PD in any HV installation system.

In this paper, investigative findings on electric field distribution and PD inception voltage in Epoxy-resin as they relate to cavity size are presented.

II. TEST SAMPLE MODEL

The model considered in this research is similar to that employed in [5] as presented in Fig. 1. It comprises of a solid dielectric epoxy-resin material with a spherical air-filled cavity positioned at the middle of the insulation bulk. The geometrical parameters of the test sample are presented in Tables I, while the material properties are given in Table II.

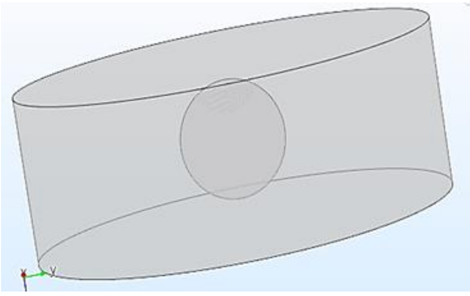

Fig. 1. 3D Representation of Test Sample Model

TABLE I. MODEL'S GEOMETRICAL SPECIFICATION

Parameter	Specification (mm)
Insulation thickness	3
Length of insulation	10
Cavity diameter	1

TABLE II. MATERIAL PROPERTIES

Component	Material	Conductivity (Sm^{-1})	Relative Permittivity
Electrode	Copper	5.998×10^7	1

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Insulation	Epoxy resin	1×10^{-18}	5.2
Cavity	Air	1×10^{-100}	1

To model the electric field distributed over the epoxy-resin insulation, a single phase 18kV sinusoidal voltage at 50Hz power frequency was applies to the upper part (HV) of the model, while the zero potential was applied to the ground. The model's geometrical configuration allows for a 2D axisymmetric modeling. But for improved visualization of the distributed field, the test sample model is developed and implemented in 3D (see Fig. 1). Consequently, the meshed pattern of the model is brought in Fig. 2. For a reasonable simulation time, Fine, Free Triangular mesh element was employed for the model. The mesh details are given in Table III.

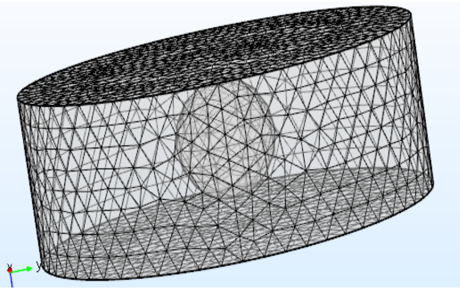


Fig. 2. 3D Meshed Pattern of Test Sample Model

TABLE II. MESH PROPERTIES

Parameter	Value	SI Unit
Maximum size of element	185×10^{-3}	mm
Minimum size of element	625×10^{-5}	mm
Maximum growth of element	125×10^{-2}	—
Curvature factor	25×10^{-2}	—
Resolution of narrow region	100×10^{-2}	—

To evaluate the field distribution in the model, the 'electric currents (ec)' component of the AC/DC module in component of the COMSOL software utilized. An optimized simulation time adopted from [2] was for this model as the models are almost similar in terms of their operations. Upon completion of domain and material assignments to all components of the model, the model is simulated for a 'Time Dependent' study for 0.05s with a time step of 0.025s. The distribution of electric field in the test model is solved using finite element method in the Multiphysics software.

A. *Field Computation*

The field model of the non-uniform epoxy-resin material is calculated via the combination of the current continuity and Poisson equations explained by the equations 1 and 2 [5] and [8]:

$$\vec{\nabla}.\vec{D} = \rho_f \quad (1)$$

$$\vec{\nabla}.\vec{J_f} + \frac{\partial \rho f}{\partial t} = 0 \quad (2)$$

where $\vec{D}$ represent the displacement field in the model, and $\vec{J_f}$ and ρ_f, are the free current and free charge densities respectively [9]. The electric, $\vec{E}$, and displacement, $\vec{D}$, fields are expressed in terms of the material property, ε, as [6]:

$$\vec{D} = \varepsilon\vec{E} \quad (3)$$

where,

$$\vec{E} = -\vec{\nabla}U \quad (4)$$

U represents the electric potential, a scalar quantity at general position.

Recently, FEA software are capable of solving the Poisson's type electrostatic equation over the model geometry. This is attained by inputting equations (3) and (4) into equation (1), and substituting the volume charge density, ρ, in place of the free charge density, ρ_f [6] and [10]:

$$\vec{\nabla}^2 U + \frac{\rho}{\varepsilon} = 0 \quad (5)$$

Since $\vec{Jf}$ is the product of the electric field, $\vec{E}$, and electric conductivity, σ, using equations (1), (3) and (4), equation (2) is then expressed as:

$$\vec{\nabla}.\left(\sigma\vec{\nabla}U - \varepsilon_0\varepsilon_r\vec{\nabla}\frac{\partial U}{\partial t}\right) = 0 \quad (6)$$

Equation (6) is solved using FEA method in COMSOL Multiphysics software to calculate the model's potential voltage. The applied sinusoidal voltage is expressed as [2]:

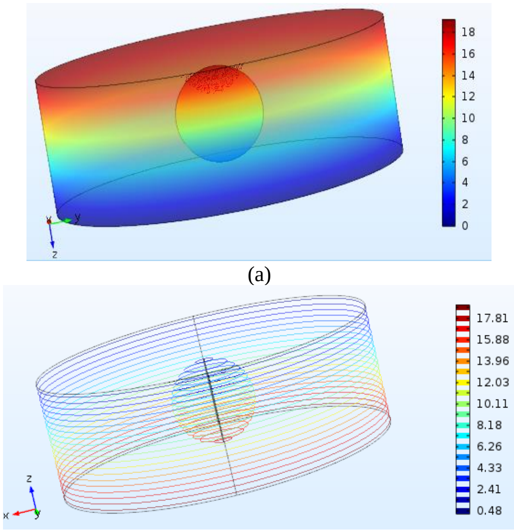
$$U = U_{peak} * \sin 2\pi f\, t \quad (7)$$

where U_{peak} and f represent the applied voltage amplitude and frequency respectively.

III. RESULTS AND DISCUSSIONS

Fig. 3a shows the volume plots of the electric field distributed across the test sample model. The field intensity is seen to be highly concentrated at the upper half of the cavity towards the electrode. This distribution is anticipated considering the variation in material property and its proximity to the source external field. The field intensity is seen to be in a receding state toward the bottom half of the cavity. The field gradually reduces to almost zero level at the ground electrode. Fig. 3b explains the distribution of potential field in the insulation system. It can be observed that both the electric and potential field distributions are much concentrated towards the HV electrode, and decreases gradually to zero. The electric potential lines are seen to be closely concentrated around the air-filled cavity than the insulation bulk. Again, this is due to the low level of permittivity inside the cavity with respect to the surrounding insulation.

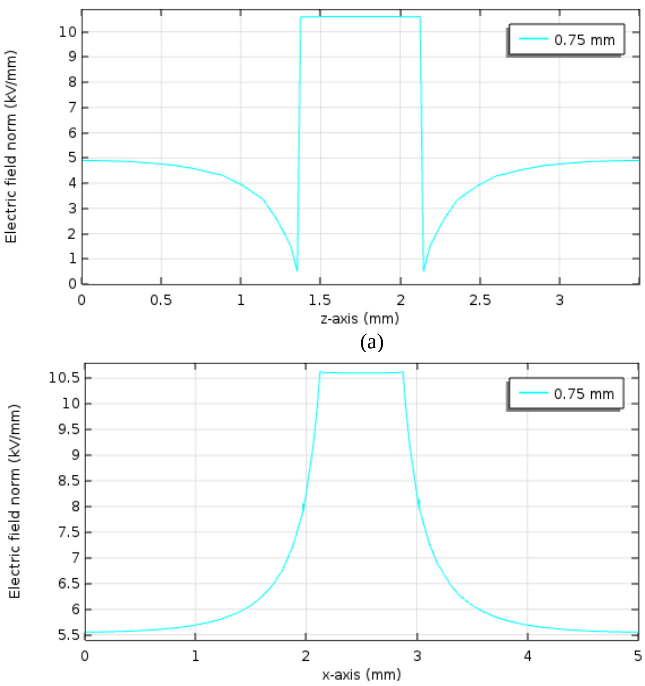
Fig. 4 shows the axial and radial distributions of electric field in the test sample model. In Fig. 4a, the field magnitude is seen to maximum the cavity as compared to the surrounding dielectric material, and is attributed to low permittivity level of the insulation-bounded cavity. In the radial distribution shown plot brought in Fig. 4b, there is no concentration of charge along the cavity wall as compared to Fig. 4a.



(a)

(b)

Fig. 3. Field Distribution of the test model (a) Electric (b) Potential Field distribution



(a)

(b)

Fig. 4. Electric Field Distribution in Insulation bulk
(a) Axial (b) Radial

An increase in the cavity diameter reduces the axial electric field intensity due to the reduction in the charge density at the cavity-dielectric boundary. Also, increased proximity of HV electrode causes the electric field to become higher on the cavity surface than inside it.

In Fig. 5, the impact of cavity diameter on electric field strength is shown. The cavity is located at the middle of the insulation bulk. It can be observed that the average field magnitude increases as the cavity sizes descreases, and vice-versa. However, a quick drop in field magnitude in experienced when the cavity diameter increses above 2mm. This can be attributed to the increased cavity space in relation to the rest of the insulation.

The impact of cavity size on inception field is brought in Fig. 6. The inception field decreases as the cavity diameter increases. For cavities with smaller diameters, the distance between the start electron and the cavity surface parallel to the electric field is smaller, and consequently a higher inception field is need to ignite a PD event.

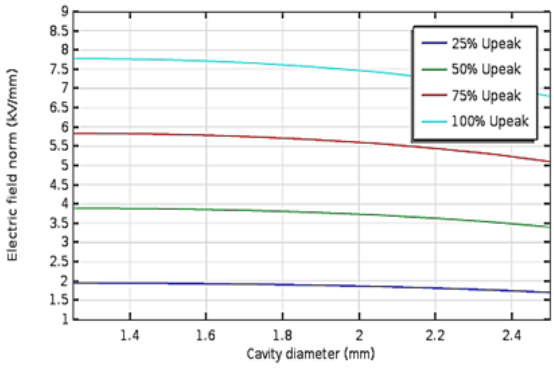


Fig. 5. Impact of cavity diameter on Electric Field

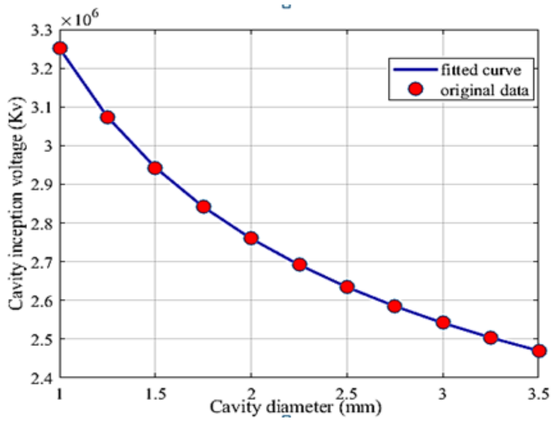


Fig. 6. Effect of cavity diameter on Inception voltage

IV. Conclusion

This paper has presented an investigative study on the impact of cavity size on the field distribution across a solid insulation system deployed for HV application. Similarly, the inception voltage as a function of cavity diameter has been studied. A 3D model of a cavitated solid dielectric, epoxy-resin has been developed. The distribution of electric field in the model was simulated, and analysis were conducted for different cavity diameters. Also, the axial and radial field distributions were obtained and the relationship between PD inception voltage and void diameter was also established. It can be inferred from the results obtained that the average cavity field, electric, is greatly dependent upon the ccavity size.

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