Electric Field Effect on Metallic Particle in Single Phase Dielectric Coated Gas Insulated Busduct Using Finite Element Method

Narapareddy Ramarao*, J.Amarnath, B.Pedda Veeru*, Sampath.J*, Anil Kumar.A***

*(Department of Electrical and Electronics Engineering, Nigama Engineering College, KarimNagar-505186)
**(Department of Electrical and Electronics Engineering, JNTUH College of Engineering, Hyderabad-5000072)

ABSTRACT

Present paper analyses the effect of electric field on the movement of metallic particles inside a single phase dielectric coated Gas Insulated Busduct(GIB). A reasonable second order differential equation has been derived for a metallic particle motion for ascertaining its trajectory. The particle motion depends on electric field and this field at the instantaneous particle locations can be computed by using analytical or analog or numerical methods. In this paper Finite Element Method(FEM) has been used for calculating the electric field, RK 4th order method is used for solving particle motion equation and thereby movements of metallic particle are computed. These particle movements are compared with the particle movements obtained by using analytically calculated electric fields. From the results it is observed that the particle maximum movements with FEM calculated electric fields are slightly more than the maximum movements obtained with analytically computed electric fields. The simulation is carried out for various bus configurations with different aluminum and copper particles. The results have been analyzed and presented in this paper.

Keywords - Particle Contamination, Particle trajectory, Gas Insulated Busduct, Dielectric coating, Finite Element Method.

1. INTRODUCTION

In a Gas Insulated Busduct(GIB) and Gas Insulated Transmission Lines(GITL), all live parts are enclosed in compressed Sulphur Hexa Fluoride(SF_6) gas chambers. Even though SF_6 exhibits very high dielectric strength, the withstand voltage of SF_6 within the Gas Insulated Substation(GIS) is drastically reduced due to the presence of metallic particles. The electrical insulation performance of GIB is adversely affected by metallic particle contaminants as a conducting particle can short-circuit a part of the insulation distance, and thereby initiates a breakdown[1],[4]; especially its electrostatic force can cause the particle to bounce into the high field region near the high voltage conductor[2]. Investigations revealed that 20% of failures in GIS are due to the existence of various metallic contaminations in the form of loose particles[9].

In spite of great care taken at the time of manufacturing of GIS equipment metallic particle contaminants are inevitable in installed systems. Several methods of conducting particle control and deactivation are proposed[3] and some of these are: 1. Electrostatic trapping 2. Use of adhesive coating to immobilize particles 3. Discharging of conducting particles through radiation 4. Coating conducting particles with insulating films 5. Dielectric coating on the inner surface of the outer enclosure.

The enclosures of Gas Insulated Busducts may be coated with a dielectric material as coating decreases the degree of conductor's surface roughness and the high local electrical fields[3],[7],[8]. Coating thickness has been varied from a few microns to several millimeters.

The specific work reported deals with the effect of electric field on the particle trajectories in a single phase dielectric coated Gas Insulated Busduct. A second order differential equation of particle motion is derived from the dynamics of the particle and solved iteratively using Runge-Kutta 4th order method. The electric field in Gas Insulated Busduct can be calculated using Analytical methods or Analog methods or Numerical Methods. In this paper Finite Element Method is used for calculating electric fields at the particle locations and thereby its effect on the movements of metallic particles is analysed. The metallic particle movements with FEM field calculations are compared with the movements obtained using analytically computed electric fields. This paper also analyses the improvement in dielectric performance, reduction of the particle maximum movements and increase of the charged particle lift-off field by coating the GIB.

2. MODELLING TECHNIQUE OF GIB

For this study a typical single phase gas insulated busduct comprising of a conductor with dielectric coated outer enclosure filled with SF_6 gas as shown in fig.1 is considered. A wire like particle is assumed to be at rest on the dielectric coated inner surface of GIB enclosure. When a voltage is applied to single phase GIB, the particle resting on inner surface of dielectric coating acquires charge in the presence of high electric fields and high gas pressures, mainly due to two different particle charging mechanisms[3],[7]. They are 1. Conduction through dielectric coating 2. Micro discharges between the particle and dielectric coating. An appropriate particle charge and electric field causes the particle to lift and begins to move in the direction of the electric field after overcoming the forces due to its own weight and drag[3],[4]. The simulation considers several parameters like the macroscopic field at the location of the particle, its weight, viscosity of the gas, Reynold's number, drag coefficient and coefficient of restitution[5],[6] on its impact to the enclosure. During the return flight, a new charge on the particle is assigned, based on the instantaneous electric field.

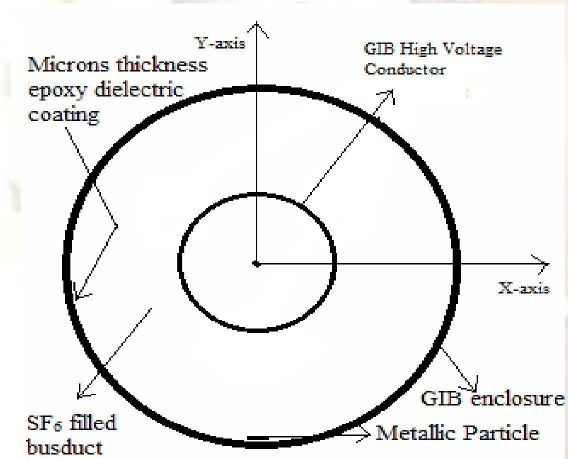

Fig.1 Typical single phase dielectric coated Gas Insulated Busduct

The equation of the motion for can be expressed as,

$$m\frac{d^2y}{dt^2} = F_e - mg - F_d \quad (1)$$

Where m = mass of the particle, y = displacement in vertical direction, Fe = Electrostatic force, g = gravitational constant, F_d = Drag Force.

The motion equation using all forces can therefore be expressed as[3-5]:

$$m\,\ddot{y}(t) = \left[\frac{\Pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{r}\right)-1} \times E(t)\right.$$

$$\left. - mg - \dot{y}(t)\Pi r\left[6\mu K_d\left(\dot{y}\right) + 2.656\left[\mu P_g l\,\dot{y}\right]^{0.5}\right]\right] \quad (2)$$

Where E(t) is electric field intensity at time 't' at the particle location.

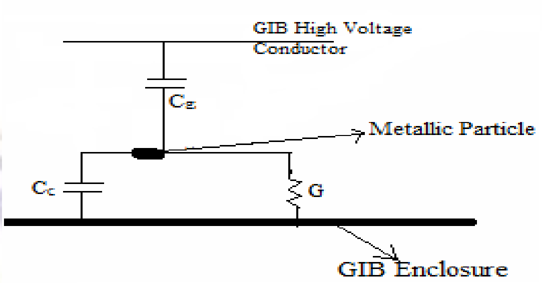

Fig.2 Circuit model of particle charging through the dielectric coating.

The circuit model of particle charging through the dielectric coating is as shown in Fig. 2. C_g represents capacitance between the phase conductor and the particle whereas 'Cc' represents capacitance between the particle and the enclosure. The conductance 'G' represents the part of the dielectric coating where the Charging current is flowing.

By using particle motion equation, the lift-off field 'E_{lo}' of the metallic particle can be obtained as,

$$E_{lo} = K\left[\left(1+\frac{C_c}{C_g}\right)^2 + \frac{1}{R^2\omega^2 C_g^2}\right]^{0.25}\left(\frac{\rho_c T}{S}\right)^{0.5} \quad (3)$$

Where 'K' is a constant. 'C_g' is effective capacitance between three phase conductors and metallic particle. 'ω' is angular velocity, 'T' is thickness of dielectric coating, 'S' is contact area between particle and dielectric coating, 'ρ_c' is resistivity of dielectric material, 'R' is resistance between particle and GIB enclosure and 'C_c' is capacitance between particle and GIB enclosure.

3. SIMULATION OF PARTICLE MOTION

The study of the motion of moving metallic particles in GIB requires magnitude of the charge acquired by the particle and electrostatic field present at the metallic particle location. The electric field in GIB is calculated using Analytical Method[8],[9] and Finite Element Method[11]-[13] separately.

3.1 Analytical Method

In analytical method ambient electric field at any time in single phase Gas Insulated Busduct can be calculated by using following equation,

$$E(t) = \frac{V \sin \omega t}{\left[R_e - y(t) ln \left[\frac{R_e}{R_c}\right]\right]} \quad ((3)$$

Where V Sin ωt is the supply voltage on the inner electrode, R_e is the enclosure radius, R_c is the inner conductor radius, y(t) is the position of the particle which is moving upwards, the distance from the surface of the enclosure towards the inner electrode.

3.2 Finite Element Method

Figure 3 depicts basic concept for discretisition of Gas Insulated Busduct space for calculation of ambient electric field at any time in single phase Gas Insulated Busduct using Finite Element Method[13].

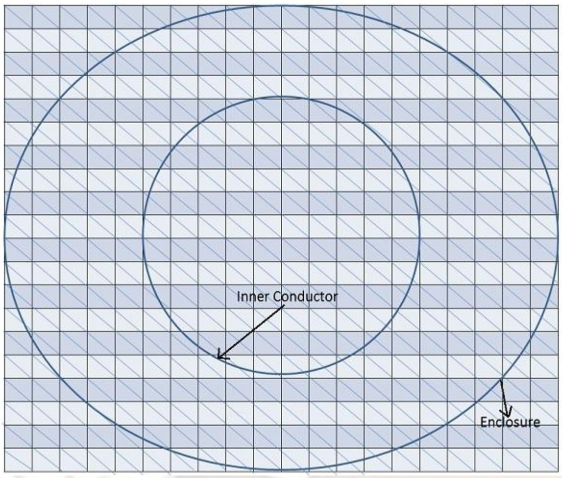

Fig. 3: Finite element mesh for calculating potentials at finite element nodes.

The Total Energy(W) associated with the assemblage of all elements in Gas Insulated Busduct is,

$$W = \sum_{e=1}^{N} w_e = \frac{1}{2}\, \varepsilon [V]^T [C][V] \quad (4)$$

Where 'N' is number of elements, 'V' is node voltage matrix of 'n' nodes and 'C' is overall or global coefficient matrix.

In Finite Element Method, the solution region has minimum total energy satisfying the laplace's or poission's equation. So, partial derivatives of 'W' with respect to each nodal value of potential must be zero.

$$\frac{\partial W}{\partial V_1} = \frac{\partial W}{\partial V_2} = \cdots \quad \frac{\partial W}{\partial V_n} = 0 \quad (5)$$

In general, simplifying the finite element mesh,

$$\sum_{i=1}^{n} V_i C_{ik} = 0 \quad (6)$$

Where i is number of nodes and k=1,2,3,………n. So, a set of 'n' simultaneous equations are obtained and solving the above simultaneous equations using band matrix method for unknown node voltages(V_f),

$$[V_f] = [C_{ff}]^{-1}(-[C_{fp}][V_p]) \quad (7)$$

Where V_f is free node voltage matrix, V_p prescribed or fixed node voltage matrix, C_{ff} free node global coefficient matrix and C_{fp} is free to prescribed nodes global coefficient matrix.

Electric Field intensity at any point in Gas Insulated Busduct is calculated by using following equation,

$$E = -Grad\, V \quad (8)$$

3.3 Monte-Carlo Technique

The motion equation of metallic particle is solved by using RK 4th Order method and it gives the particle movement in the radial direction only. The Axial movement of the metal particle is calculated by using Monte-carlo Technique based on the works of J.Amarnath et al[5],[6]. Computer simulations of motion for the metallic wire particles were carried out using Advanced C Language Program in GIB with inner conductor diameter 55mm and enclosure diameter of 152mm for 75kV,100kV, 145kV, 175kV and 220kV applied voltages. Aluminum and copper wire like particles were considered to be present on the enclosure surface.

4. RESULTS AND DISCUSSIONS

The results are obtained by solving the metallic particle motion equation using RK 4th order method and Monte-Carlo Technique for aluminium and copper particles. The Electric fields are determined by with Analytical Method as given by equation (3) and with Finite Element Method by using equations(7) and (8).

Table I and Table II are showing the movement patterns of aluminium and copper particles for power frequency voltages. 289 finite element nodes are considered in Gas Insulated Busduct space for calculating node potentials using Finite Element Method. The radius of aluminium and copper particles in all cases are considered as 0.01 mm, length of the particle as 10 mm, restitution coefficient is 0.9 and SF_6 gas pressure is 0.4MPa.

During application of power frequency voltage, the moving metallic particle makes several impacts with the enclosure and the maximum radial movement increases with increase of applied voltage. Table I shows the maximum radial movements for aluminium and copper particles for different voltages with analytical and FEM calculated electric fields. For Aluminium metallic particles with analytically calculated electric field, the maximum radial movement is 3.06mm and with Finite Element Method is 3.10mm for 75kV and these radial movements increase with increase of applied voltage. The maximum radial movement is reaching 14.81mm and 14.90mm with analytical and with FEM calculated electric fields respectively at 220kV. For Copper particles, the radial movement is 1.27mm with analytically calculated field and 1.30mm with FEM calculated electric field at 75kV and this radial movement is increasing with increase of applied voltage and reaching maximum value of 7.50mm and 7.74mm with analytically and FEM calculated electric fields respectively for 220kV.

Table I Maximum Radial Movements of aluminum and copper particles with analytically and FEM calculated electric fields.

Sl.No.	Volt-age (kV)	Particle type	Max. Movement with Analytical Field(mm)	Max. Movement with FEM Field(mm)
1	75	Al	3.06	3.1
		Cu	1.27	1.3
2	100	Al	4.75	4.77
		Cu	2.02	2.06
3	132	Al	7.64	7.74
		Cu	3.02	3.06
4	145	Al	8.77	8.79
		Cu	3.43	3.47
5	175	Al	11.3	11.36
		Cu	4.92	4.95
6	220	Al	14.81	14.9
		Cu	7.5	7.74

Table II Maximum Axial Movements of Al and Cu particles with analytically and FEM electric fields.

Sl. No.	Volt-age(kV)	Particle type	Max. Movement with Analytical	Max. Movement with FEM Field(mm)
1	75	Al	54.87	62.4
		Cu	28.55	31.69
2	100	Al	57.87	76.5
		Cu	38.35	43.94
3	132	Al	97.02	82.81
		Cu	44.84	66.56
4	145	Al	136.22	124.47
		Cu	55.94	68.8
5	175	Al	54.94	57.78
		Cu	44.96	64.2
6	220	Al	71.95	68.6
		Cu	78.34	90.72

Similarly for Aluminium particles the maximum axial movement with analytical calculated electric field is 54.87mm and with FEM calculated electric field is 62.4mm for 75kV. The maximum axial movements of Aluminium particles are increasing with increase of voltage up to 145kV and decreasing with increase of voltage to 175kV and again axial movement is increasing with increase of voltage to 220kV. For 220kV maximum axial movements are reaching 73.8958mm and 98.5393mm for electric fields calculated with Analytical and FEM calculated electric fields respectively for Alumimum particles. For Copper particles at 75kV, the maximum axial movement is 28.55mm and 31.69mm with analytical and FEM calculated electric fields respectively. The maximum axial movements of Copper particles are increasing with increase of voltage for up to 145kV and after these maximum axial movements are decreasing with increase of voltage for 175kV, then after again maximum axial movement is increasing with increase of voltage. At 220kV maximum axial movements are reaching 78.34mm and 90.72mm for analytical and FEM calculated electric fields respectively. Table II represents Aluminium and Copper particle maximum axial movement for different voltages with analytical and FEM calculated electric fields.

Fig. 3 to Fig. 10 show the radial movement patterns of aluminum and copper particles using Analytical and Finite Element Method electric fields for power frequency voltages of 100kV and 220kV.

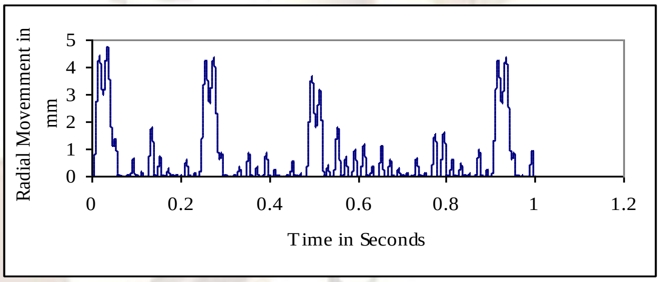

Fig.3 Al particle radial movement for 100kV with analytical electric field

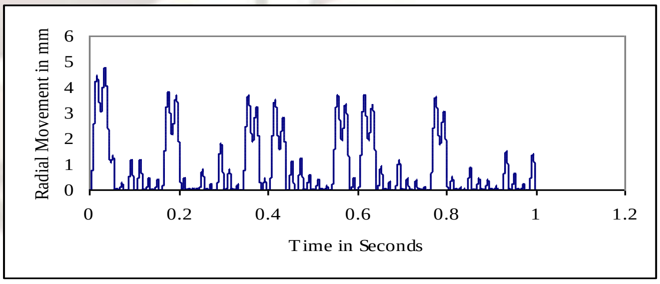

Fig.4 Al particle radial movement for 100kV with FEM electric field

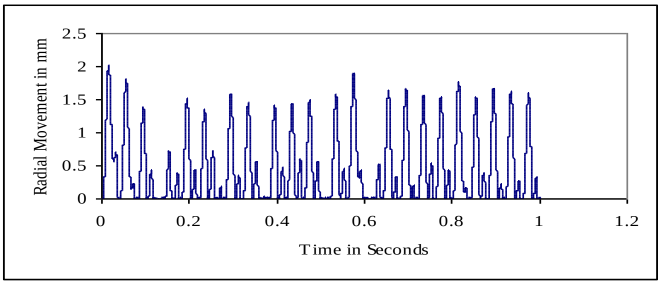

Fig. 5 Cu particle radial movement for 100kV with analytical electric field

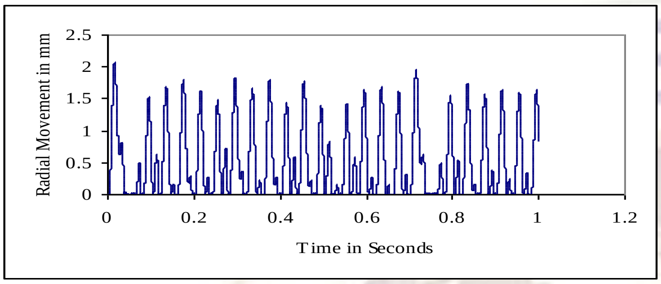

Fig.6 Cu particle radial movement for 100kV with image FEM electric field

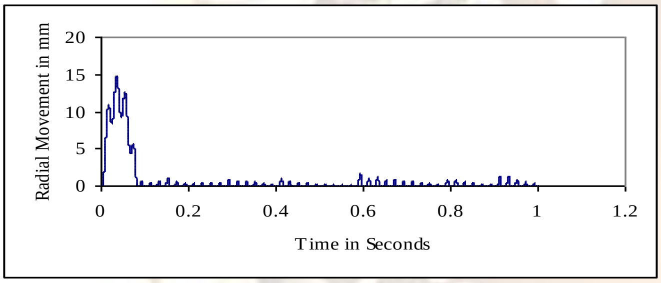

Fig.7 Al particle radial movement for 220kV with analytical electric field

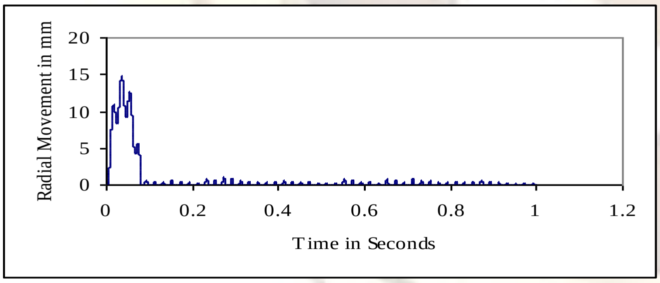

Fig.8 Al particle radial movement for 220kV with FEM electric field

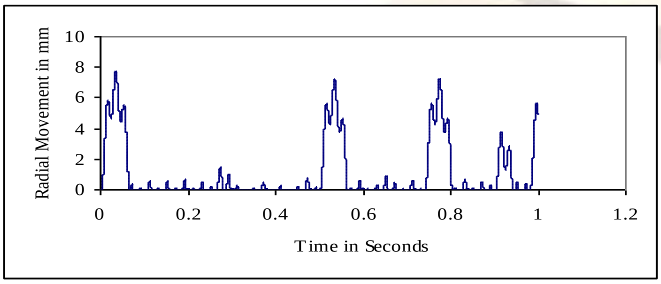

Fig.9 Cu particle radial movement for 220kV with analytical electric field

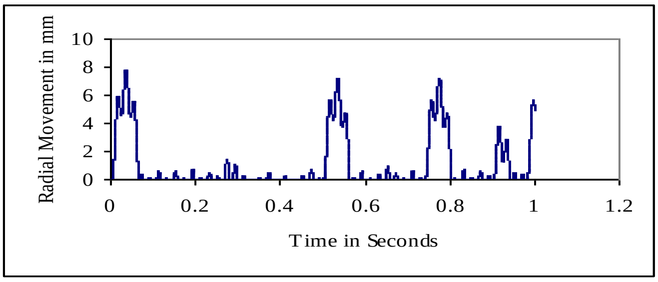

Fig.10 Cu particle radial movement for 220kV with FEM electric field

5. CONCLUSION

A reasonable second order differential equation has been formulated to simulate the wire like particle trajectory under the influence of electric fields calculated using Finite Element Method in single phase GIB. When an electrostatic force on the metallic particle due to applied voltage exceeds the gravitational and drags forces, the particle lifts from its position and moves into the inter electrode gap. From the results it is observed that particle movements with the electric fields calculated using Finite Element Method are slightly more than the particle movements obtained using analytically computed electric fields. Also, it is noted that aluminum particles are more influenced by the voltage than copper particles due to their lighter mass and this causes the aluminum particle to have greater charge-to-mass ratio. Monte-Carlo simulation is also adopted to determine the axial movements of the particle in the busduct. The dielectric coating of epoxy resin on inner surface of the enclosure with a light shade of micron thickness improves the GIB dielectric strength. Also it is noted that the particle maximum movements are decreased and lift-off field is increased with dielectric coating. All the above investigations have been carried out for various voltages under power frequency. The results obtained are analyzed and presented.

ACKNOWLEDGMENT

The authors are thankful to the managements of Nigama Engineering College, Karim Nagar, and JNTUH University, Hyderabad, for providing facilities and to publish this work.

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