Electric Field Effect On Particle Trajectory In Three Phase Dielectric Coated Gas Insulated Busduct Using Numerical Methods

Narapareddy Rama Rao[*], J.Amarnath[**]

[*]Department of Electrical and Electronics Engineering, Nigama Engineering College, Karim Nagar, AP, INDIA
[**]Department of Electrical and Electronics Engineering, JNTUH College of Engineering, Hyderabad, AP, INDIA

ABSTRACT

Free metallic conducting particles in Gas Insulated Busduct(GIB) may cause loss of as much as 90% of the gas dielectric strength. Research studies revealed that 20% of failures in Gas Insulated Substations (GIS) are due to presence of free metallic contaminations in the form of loose particles. Therefore, the presence of free metallic particles in Gas Insulated Busduct(GIB) operating at high electric fields can be a problem. If these particles are eliminated from GIB, then the reliability of compressed Gas Insulated Substation can be improved. The purpose of this paper is to develop techniques for formulating the basic equations that will control the movement of metallic particles in a dielectric coated Gas Insulated Busduct. Analytical and numerical techniques have been used to describe the effect of the ambient electric field on the movement of metallic particle in GIB. The simulation has been carried out to obtain the particle trajectories at various voltages for particles of Aluminum and Copper. The results have been presented and analyzed in this paper.

Keywords - Dielectric coat, Gas Insulated Busduct, Contaminated metallic particle, Finite Element Method, Metallic particle trajectory.

I. INTRODUCTION

Gas Insulated Substation (GIS) suffer from certain drawbacks and one of them is the outage due to seemingly innocuous conducting particles, which accounts for nearly 20% of the GIS failures. These particles may have any shape or size, may be spherical or filamentary (wire like) or in the form of fine dust. Flash over in a GIS is, in general, associated with longer outage times and greater costs than in a conventional air insulated substation. The conducting particles can either be free to move in the Gas Insulated Busduct(GIB) or they may stick to an energized electrode or to an enclosure surface. Free conducting particles in GIB could reduce the insulation strength drastically as they can short-circuit a part of the insulation distance, and thereby initiates a breakdown and if these particles could be eliminated, then this would improve the reliability of compressed gas insulated substations[1,2,3]. At the time of manufacturing of GIS equipment, care should be taken to ensure that all components are free from free metallic particles. However, metallic contaminants are inevitable in installed systems. The most common causes are mechanical vibrations during shipment and service, thermal expansion/contraction at expansion joints. Several methods of conducting particle control and deactivation have been proposed[4,5] and one of them is dielectric coating on the inner surface of the outer enclosure.

The dielectric coatings can improve the insulation performance by reducing the charge on the particle and thereby increase the lift off field[2,6,7]. The work reported in this paper deals with the techniques, which will formulate the basic equations that will govern the movement of metallic particles like aluminum and copper and also the maximum movement is to be reduced for increasing the dielectric strength of gaseous Insulation. The results are analyzed and presented.

II. MODELLING TECHNIQUE

For this study a typical three phase common enclosure horizontal busduct comprising of three inner conductors A, B and C 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 enclosure. When a three phase voltage is applied to three phase GIB, the particle acquires charge in the presence of high electric fields and low gas pressures mainly due to two different particle charging mechanisms. They are 1. Conduction through a dielectric coating 2. Micro discharges between the particle and coating [7].

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[5,6,8].

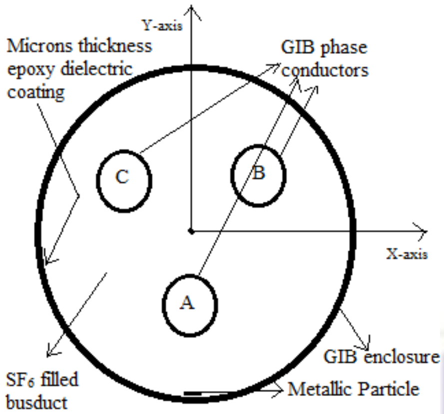


Figure 1. Typical three phase common enclosure Gas Insulated Busduct

The simulation considers several parameters like the macroscopic field at the location of the particle, its length, radius and weight, viscosity of the gas, Reynold's number, drag coefficient and coefficient of restitution[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.

A conducting metallic particle moving under the external electric field will be subjected to Electrostatic force (F_e), Gravitational force (F_g) and Drag force (F_d).

The equation of the motion for can be expressed as,

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

Where m = mass of the particle, y = displacement in vertical direction, g = gravitational constant.

The motion equation using all forces can therefore be expressed as[4-8]:

$$m\,\ddot{y}(t) = \left[\frac{\Pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{r}\right)-1} \times E(t)\right] - mg - \dot{y}(t)\Pi r\left[6\mu K_d\left(\dot{y}\right) + 2.656\left[\mu P_g l \dot{y}\right]^{0.5}\right] \qquad (2)$$

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

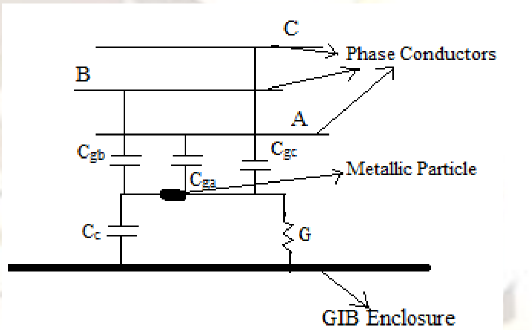
The circuit model of particle charging through the dielectric coating is as shown in Fig. 2.

C_{ga} ,C_{gb} and C_{gc} represents capacitances between the three phase conductors and the particle, '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,

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

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. It



can be noted that 'E_{lo}' is approximately proportional to square root of the thickness and resistivity of the dielectric.

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

The particle motion equation is a second order non-linear differential equation and it is solved by using Runge- Kutta 4th Order Method.

III. SIMULATION OF METALLIC PARTICLE

For the study of the motion of moving metallic particle in Gas Insulated Substation requires magnitude of the charge acquired by the particle and electrostatic field present at the metallic particle location. The electric field at the metallic particle location is calculated analytical method, Finite Difference Method[9] and also by using Finite Element Method[9-11].

A. FINITE ELEMENT METHOD*:*

The following Figure 3 depicts the basic concept for application of Fnite Element Method in the required space for finding potentials at the element nodes.

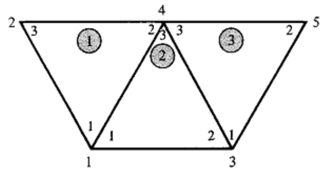


Fig. 3: Finite element mesh for calculating potentials at finite element nodes.

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,

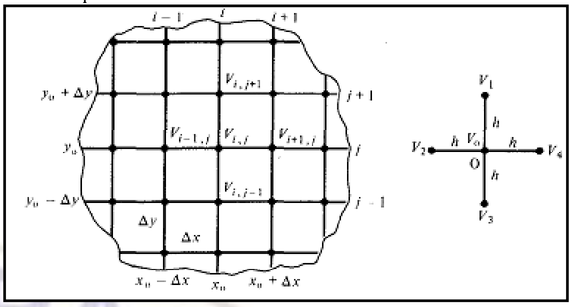
$$E = -Grad\,V \quad (8)$$

B. FINITE DIFFERENCE METHOD:

Figure 3.6 Finite difference solution pattern

The figure 3.6 shows the finite difference solution pattern representing division of solution region into grid points and finite difference five node molecule.

$$V_{i,j} = \frac{1}{4}\left[V_{i+1,j} + V_{i-1,j} + V_{i,j+1} + V_{i,j-1}\right] \quad (9)$$



The finite difference approximation to poission's equation applied to Gas Insulated Busduct solution region for five-node is:

$$V_o = \frac{1}{4}[V_1 + V_2 + V_3 + V_4] \quad (10)$$

The above equation shows the average value property of Laplace equation. Using Band Matrix Method[105] to all free nodes in solution region results in a set of simultaneous equations of the form

$$[A][V] = [B] \quad (11)$$

Where $[A]$ is sparce matrix, $[V]$ is free node potentials and $[B]$ is column matrix of potentials at fixed nodes of solution region. Therefore unknown potentials at free nodes is,

$$[V] = [A]^{-1}[B] \quad (12)$$

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

$$E = -\nabla V \quad (13)$$

C. ANALYTICAL METHOD:

Analytically ambient electric field 'E' at any time in three phase GIB can be calculated by using following equation,

$$E = \frac{1}{\ln(h/Rc)}\left[V_a\left[\frac{1}{h-x}\right] + \left(\frac{Cos\,\theta_2}{R_{bx}}\right)(V_b + V_c)\right] \quad (14)$$

Where V_a, V_b, and V_c are phase voltages of A, B, and C conductors respectively, R_c is the high voltage conductor radius, R_{bx} is distance between B phase conductor and particle location, 'Θ_2" is the angle between R_{bx} and vertical axis at B or C phase conductor and 'x' is the distance from enclosure inner surface to the position of the particle which is moving upwards.

IV. RESULTS AND DISCUSSION

The motion equation of metallic particle is solved by using RK 4th Order method and it gives 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]. The Electric fields are determined by using equations(12) and (13) for Finite Difference Method, Finite Element Method as given by equations (7) and (8) and with Analytical Method using equation (14).

Computer simulations of motion for the metallic wire particles were carried out using Advanced C Language Program for GIB with high voltage conductors diameter 64mm and enclosure diameter of 500mm for 220kV, 300kV, 400kV, 500kV and 600kV applied voltages. Aluminum and copper wire particles were considered for simulations.

Table I and Table II are showing the movement patterns of aluminium and copper particles for various power frequency voltages. 289 nodes are considered for finite difference and finite element methods in dielectric coated three phase Gas Insulated Busduct space for calculating node potentials and thereby electric field at respective nodes. The radius of aluminium and copper particles in all cases are considered as 0.01mm, length of the particle as 12mm, 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. For Aluminium metallic particles the maximum radial movement is 2.39mm, 8.69mm and 10.75mm with analytical, FDM and FEM calculated field for 220kV and the radial movement is increasing with increase of applied voltage and reaching maximum movement of 8.38mm, 34.96 and 35.66mm with analytical, FDM and FEM calculated field at 600kV respectively.

Table I Maximum Radial Movements of aluminum and copper particles.

Voltage in kV	Type of Particle Material	Max. Radial Movement (mm) with Analytical Method	Max. Radial Movement (mm) with FDM	Max. Radial Movement (mm) with FEM
220	Al	2.39	8.69	10.75
	Cu	0.57	3.11	4.14
300	Al	3.19	13.91	16.29
	Cu	1.01	5.76	7.63
400	Al	4.29	21.06	25.63
	Cu	1.78	9.58	12.35
500	Al	6.41	27.57	32.93
	Cu	2.42	14.31	17.66
600	Al	8.38	34.96	35.66
	Cu	3.19	18.61	24.36

For copper metallic particles the radial movement for electric fields at 220kV is 0.57mm, 3.11mm and 4.14mm with analytical, FDM and FEM calculated fields. For copper particles also, the radial movement is increasing with increase of applied voltage and reaching maximum value of 3.19mm, 18.61mm and 24.36mm with analytical, FDM and FEM calculated fields respectively for 600kV. Table I show the maximum radial movements for aluminium and copper particles for different voltages with analytical, Finite Difference and Finite Element calculated electric fields.

Table II Maximum Axial Movements of Aluminium and Copper particles.

Voltage in kV	Type of Particle Material	Max.Axial Movement (mm) with analytical method	Max.Axial Movement (mm) with FDM	Max.Axial Movement (mm) with FEM
220	Al	52.98	192.26	195.40
	Cu	8.48	49.69	59.04
300	Al	73.55	275.43	273.32
	Cu	15.32	84.04	105.18
400	Al	95.90	418.75	476.38
	Cu	22.59	146.32	197.61
500	Al	127.09	503.80	555.92
	Cu	36.24	218.78	237.59
600	Al	149.10	423.38	541.78
	Cu	50.11	248.72	385.48

Similarly for Aluminium particles the maximum axial movement is 52.98mm, 192.26mm and 195.40mm with analytical, FDM and FEM calculated fields respectively for 220kV. The maximum axial movements of Aluminium particles are increasing with increase of voltages upto 500kV and after that it is observed that slight decrease in movements. For 800kV these maximum movements are reaching 149.10mm, 423.38mm and 541.78mm for electric fields calculated with analytical, FDM and FEM methods respectively. For Copper particles the maximum axial movements are 8.48mm, 49.69mm and 59.04mm with analytical, FDM and FEM calculated fields respectively. The maximum axial movements of Copper particles are increasing with increase of voltage and for 600kV these maximum movements are reaching 50.11mm, 248.72mm and 385.48mm for analytical, FDM and FEM calculated fields respectively. Table II represents Aluminium and Copper particle maximum axial movement for different voltages with analytical, FDM and FEM calculated electric fields.

Fig. 3 to Fig. 8 show the radial movement patterns of aluminum and copper particles using Analytical, FDM and FEM calculated fields at power frequency voltage of 400kV.

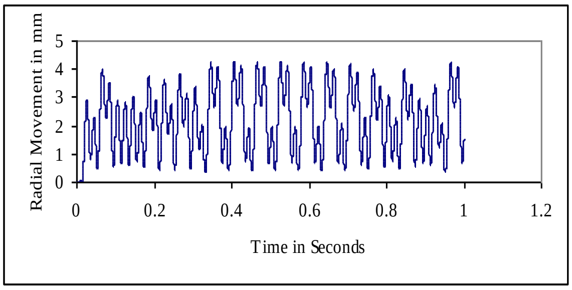


Fig.3 Al particle radial movement for 400kV with analytically calculated field

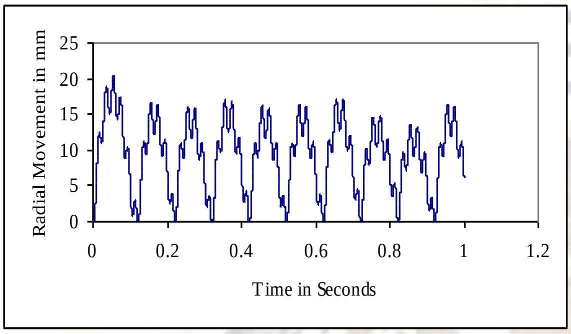


Fig.4 Al particle radial movement for 400kV with FDM calculated field

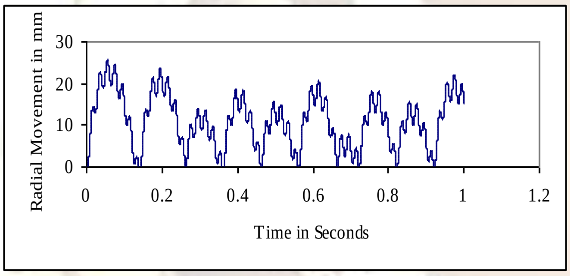


Fig.5 Al particle radial movement for 400kV with FEM calculated field

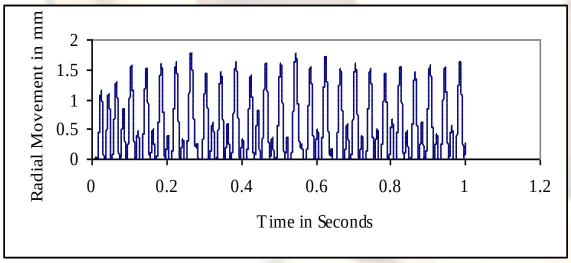


Fig. 6 Cu particle radial movement for 400kV with analytically calculated field

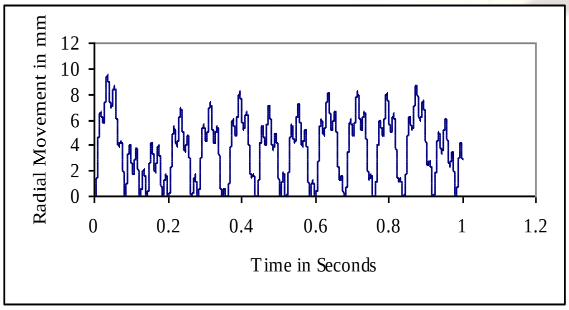


Fig.7 Cu particle radial movement for 400kV with FDM calculated field

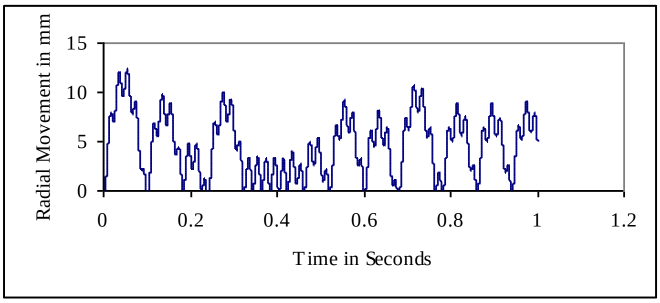


Fig.8 Cu particle radial movement for 400kV with FEM calculated field

IV. CONCLUSION

A mathematical model has been formulated to simulate the movement of wire like particle under the influence of electric field in dielectric coated three phase Gas Insulated Busduct. When an electrostatic force on metallic particle exceeds the gravitational and drag forces, the particle lifts from its position. A further increase in the applied voltage makes the particle to move into the inter electrode gap in the direction of applied field. The influence of increased voltage level on the motion of the metal particles is also investigated. For instance, it can be noted that aluminum particles are more influenced by the voltage than copper particles due to their lighter mass. This results in the aluminum particle acquiring greater charge-to-mass ratio. Monte-Carlo simulation is also adopted to determine axial as well as radial movements of particle in the busduct. Also it is observed that particle maximum movement in electric field calculated by using Finite Element Method is more than the maximum movement in electric field calculated by using analytically calculated electric field. The dielectric performance is improved by coating the inner surface of the enclosure with a light shade with micron thickness epoxy resin. This dielectric coating improves the insulation performance by reducing the charge on the particle and the maximum movement is reduced. All the above investigations have been carried out for various voltages under power frequency. The results obtained are analyzed and presented.

ACKNOWLEDGEMENT

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.

REFERENCES

[1] Anis H.and Srivastava K.D.,1989, " Breakdown characteristic of dielectric coated electrodes in SF6 as with particle contamination,", sixth Intl symposium on HVE, New Orleans, LA,USA, paper No.32-06

[2] K.D. Srivastava and R.G. Van Heeswi jk "Dielectric coatings Effect of break down

and particle movement in GITL systems", IEEE transactions on Power Apparatus and Systems, vol. PAS- 104, No.1, pp. 22-31, January 1985.

[3] J. R. Laghari and A.H.Qureshi "A Review of Particle Contaminated Gas Breakdown" IEEE Transactions on Electrical Insulation, Vol. EI-16 No.5, pp. 388-398, October 1981.

[4] H.Anis and K.D.Srivastava "Free conducting particles in compressed gas insulation", IEEE Tranctions on electrical insulation, Vol. EI-16, pp.327-338, August 1995.

[5] M.M. Morcos, S.Zhang, K.D. Srivastava, and S.M. Gubanski,"Dynamics of Metallic particle contamination in GIS with dielectric coating electrodes", IEEE Trans. Power Delivery Vol.15, pp. 455-460, 2000.

[6] J. Amarnath, B.P. Singh, C. Radhakrishna and S. Kamakshiah, "Determination of Particle trajectory in a Gas Insulated Busduct predicted byMonte-Carlo technique", IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Texas, Austin, USA, 1991 Vol.1, pp. 399-402,1991.

[7] G.V.Nagesh Kumar, J.Amarnath and B.P.Singh, "Behavior of Metallic Particles in a Single Phase Gas Insulated System with Dielectric Coated Electrodes", International Conference on Condition Monitoring and Diagnosis, Beijing, China, April 21-24, 2008.

[8] K.B.Madhu Sahu and J.Amarnath, "Effect of Various Parameters on the Movement of Metallic Particles in a Single Phase Gas Insulated Busduct with Image Charges and Dielectric Coated Electrodes", ARPN Journal of Engineering and Applied Sciences, Vol.5, No.6, June 2010, pp.52-60.

[9] Sadiku Matthew, "Elements of Electromagnetics", 4th Edition, (New Delhi,Oxford Publishers,2007), pp 694-711.

[10] J.Weiss and Z.J.Csendes "A One step Finite Element Method for Multiconductor Skin Effect Problems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No.10 October 1982.

[11] S.Cristina and M.Feliziani, "A Finite Element Technique for Multiconductor Cable Parameters Calculation", IEEE Transactions on Magnetics, Vol.25, No.4, July 1989.