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Influence of Free Metallic Particle Dimensions on Its Movement in Three Phase Common Enclosure Gas Insulated Busduct(GIB) Using Charge Simulation Method

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Abstract:- In this paper, the trajectories of free conducting particles of various sizes inside a three phase common enclosure Gas Insulated Busduct(GIB) are simulated by solving the nonlinear second order differential equation of particle motion iteratively by using RK 4^{th} Order Method. Compressed Gas Insulated Substations(GIS) consists of a conductor supported by spacers inside of Sulphur hexafluoride gas(SF_6) filled enclosure. The metallic particle contaminations in the form of loose particles adversely affect the insulation integrity and can cause failures of Gas Insulated Substations. The presence of contamination can therefore be a problem with Gas Insulated Substations operating at high electric fields. In order to determine the random movement of metallic particles, the calculation of movement in axial and radial directions was done at every time step. The simulation considers the electric field effect and various particle dimensions on the particle movement. The electric fields at the instantaneous particle locations are determined by using Charge Simulation Method(CSM). Typical results for aluminum and copper wire particle with different dimensions are described and the movements of metallic particle with charge simulation method of field calculation are compared with Analytical Method of field calculation. From the results it is observed that the particle maximum movements with analytical method of field calculation is more than charge simulation method of field calculation. Also noted that the maximum movements of metallic particles decrease with increase of particle length and radius. The results have been presented and analyzed in this paper.

Keywords:- Gas Insulated Busduct, Contaminated Metallic Particle, Particle Trajectory, Charge Simulation Method and Particle Motion Equation.

I. INTRODUCTION

Conventional air insulated substations are suffering from many problems such as pollution, meteorological difficulties, huge space requirements, safety etc. Hence, there is a need to replace the conventional transmission lines and substations with underground cable and Gas Insulated Substation (GIS) to overcome the above problems. Because of many advantages, most of the utilities and industrial units are opting for Gas Insulated Substations (GIS)[1]. Even though Gas Insulated Substations have many advantages over conventional air insulated substations, they also suffer from certain drawbacks and one of them is presence of free metallic particles inside a Gas Insulated Busduct can short-circuit a part of the insulation distance, and thereby initiate a breakdown, especially if electrostatic forces cause the particle to bounce into the high field region near the high voltage conductor[2],[3]. Flash over in a GIS is, in general, associated with longer outage times and greater costs than in a conventional air insulated substation.

This work investigates and analyses the maximum movements of aluminum and copper particles of different sizes in three phase common enclosure Gas Insulated Busduct with different high voltages class for analytical and charge simulation electric field calculation methods.

II. MODELING TECHNIQUE OF GIB

For this study a typical three phase common enclosure horizontal busduct comprising of three inner conductors A, B and C with an outer enclosure, filled with SF_6 gas as shown in fig.1 is considered.

A wire like particle is assumed to be at rest at the enclosure inner surface. When a three phase voltage is applied to three phase GIB, the particle resting on inner surface of enclosure acquires charge through electrostatic induction in the presence of electric field. An appropriate charge on the particle and electric field at the particle location causes the particle to lift and begins to move in the direction of the electric field after overcoming the forces due to gravitational force and drag force[4]. The simulation of metallic particle trajectory 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] on its impact to the enclosure. During the return flight, a new charge on the particle is assigned, based on the instantaneous electric field.

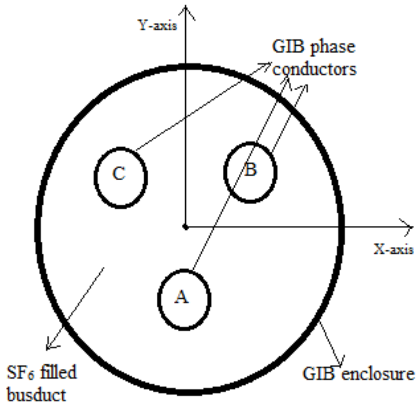

Figure 1. Typical three phase common enclosure Gas Insulated Busduct

Several authors have suggested expressions for the estimation of charge on both vertical/horizontal wires and spherical particles. The equations are primarily based on the work of Felici et al. [6]. A wire particle may lift-off horizontally under sudden applied voltages. The lift-off field E_{lo} [9] and charge q_{hw} for horizontal wire particle are

$$E_{lo} = 0.84\sqrt{\frac{r\rho g}{\epsilon_0}} \quad (1)$$

$$Q_{hw} = 2\pi \varepsilon_o r l E \quad (2)$$

Where, 'r' is the wire particle radius, ' l ' is the wire particle length, 'ρ' is density of particle material, 'g' is acceleration due to gravity, 'ε_o' permittivity of free space and 'E' is ambient electric field.
By approximating the wire to a semi-ellipsoidal of base radius 'r' and vertical length 'l' , the lift-off field E_{lo} and charge q_{vw} are

$$E_{vw} = \left[\ln\left(\frac{2l}{r}\right) - 1\right]\sqrt{\frac{r^2 \rho g}{\epsilon_0 l\left[\ln\left(\frac{l}{r}\right) - 0.5\right]}} \quad (3)$$

$$Q_{vw} = \frac{\pi \epsilon_0 l^2 E}{\left(\ln\left(\frac{2l}{r}\right) - 1\right)} \quad (4)$$

Once the wire is elevated from the horizontal to the vertical position, it acquires more charge and requires a lower electric field to remain erect. Therefore, a particle can remain active in the inter electrode gap at voltages lower than the initial lifting voltage. The charge acquired and the movement of the particle is determined for the electric fields calculated by analytical field calculation method and charge simulation method separately.
The gravitational force acting on a particle of mass 'm' is given by
$F_g = mg$ (5)
Where F_g = gravitational force on metallic particle, g = acceleration due to gravity.
The expression for the electrostatic force acting on metallic particle is given by
$F_e = KQE(t)$ (6)

Where F_e is Electrostatic Force, K is the correction factor which is less than unity, Q is the particle charge, E(t) is ambient electric field at any time 't' in a co-axial electrode system and can be calculated either by using analytical method or by using charge simulation method.
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 movement pattern of the particle is simulated by using following the motion equation:

$$m\frac{d^2y}{dt^2} = F_e - mg - F_d \qquad (7)$$

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[3],[4]:

$$m\,\ddot{y}(t) = \left[\frac{\Pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{r}\right)-1}\times E(t)\right] - mg - \dot{y}(t)\Pi r\left[6\mu K_d\left(\dot{y}\right)+2.656\left[\mu P_g l\,\dot{y}\right]^{0.5}\right] \qquad (8)$$

The above 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 studying the motion of contaminated metallic particles of different sizes in GIS requires a good knowledge of the charge acquired by the particle and electrostatic field present at the particle location. The electric field at the metallic particle location is calculated using Charge Simulation Method based on the work of Nazar H. Malik et al[7] and H.Singer[8].

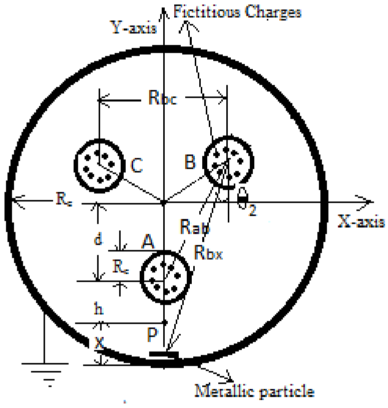

Fig. 2: Calculation of Electric Field Intensity at Point 'P' using Charge Simulation Method.

III-A. CHARGE SIMULATION METHOD:

Figure 2 depicts basic concept behind the calculation of ambient electric field at any time in three phase Gas Insulated Busduct using charge simulation method.

The Electrostatic field at point 'p(x,y)' is calculated by using the following equations:

$$E_x(t) = \sum_{i=1}^{3n}\frac{\lambda_i}{2\pi\varepsilon}\left[\frac{x-x_i}{\sqrt[3]{(x-x_i)^2+(y-y_i)^2}}\right] \qquad (9)$$

$$E_y(t) = \sum_{i=1}^{3n}\frac{\lambda_i}{2\pi\varepsilon}\left[\frac{y-y_i}{\sqrt[3]{(x-x_i)^2+(y-y_i)^2}}\right] \qquad (10)$$

Where $E_x(t)$, $E_y(t)$ are Electrostatic field components at time instant 't' along X(Horizontal) and Y(Vertical)-axes respectively, 'x', 'y' are coordinates of point 'p' where Electric field is to be calculated, 'x_i', 'y_i' are coordinates of ith fictitious charge, 'n' is the number of fictitious charges per phase, 'λ_i' is line charge density of ith fictitious charge. Fictitious charges are considered inside of each conductor of GIB for calculating electric field in Charge Simulation Method.

III-B. ANALYTICAL METHOD:

In analytical method ambient electric field 'E_y' at point 'P' in three phase Gas Insulated Busduct can be calculated by using following equation,

$$E_y = \frac{1}{\ln(h/Rc)}\left[V_a\left[\frac{1}{h-x}\right]+\left(\frac{Cos\theta_2}{Rbx}\right)(V_b+V_c)\right] \qquad (11)$$

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 4^{th} Order method and it gives movement in the radial direction only. The Axial movement of the metallic 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 Charge Simulation Method as given by equations (9) and (10) and with Analytical Method using equation (11). Computer simulations of motion for different sizes of metallic wire particles and with different GIB voltages were carried out using Advanced C Language Program.

IV-A. Effect of Electric Field:

The Gas Insulated Busduct with each high voltage conductor diameter of 64mm and enclosure diameter of 500mm is considered for simulation with 220kV, 300kV, 400kV, 500kV and 800kV applied voltages. Aluminum and copper wire like particles were considered to be present on enclosure surface.

Table I and Table II are showing the maximum movements of Aluminium and copper particles for different power frequency voltages. 32 factitious charges per phase with assignment factor of 1.5 are considered for calculating electric field with charge simulation method in three phase GIB. The radius of Aluminium and copper particles in all cases are considered as 0.15 mm, length of the particle as 12 mm, restitution coefficient is 0.9 and SF_6 gas pressure is 0.4MPa.

Table I Maximum Radial Movements of aluminum and copper particles.

Voltage	Type of Particle Material	Max. Radial Movement (mm) with CSM calculated electric filed	Max. Radial Movement (mm) with Analytically calculated electric field
220kV	Al	9.7676	12.1219
	Cu	0.0000	0.0000
300kV	Al	14.4521	19.0472
	Cu	0.0000	0.0000
400kV	Al	18.6283	26.4785
	Cu	8.9647	10.2990
500kV	Al	25.6687	29.2129
	Cu	11.6886	17.0706
800kV	Al	35.6425	40.4219
	Cu	21.8464	30.2385

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 9.7676mm with field calculated by using Charge Simulation Method and 12.1219mm with analytically calculated field for 220kV and the radial movement is increasing with increase of applied voltage and reaching maximum movement of 35.6425mm with CSM calculated field and 40.4219mm with analytically calculated field. For copper metallic particles there is no movement in radial directions for up to 300kV and for electric fields at 400kV, the radial movement is 8.9647mm with CSM calculated field and 10.299mm with analytically calculated field. For copper particles, the radial movement is increasing with increase of applied voltage and reaching maximum value of 21.8464mm with CSM calculated field and 30.2385mm analytically calculated field for 800kV. Table I shows the maximum radial movements for Aluminium and copper particles for different voltages with and without image charge effects.

Table II Maximum Axial Movements of Aluminium and Copper particles.

Voltage	Type of Particle Material	Monte-Carlo(1^0) Max.Axial Movement(mm) with CSM calculated field	Monte-Carlo(1^0) Max.Axial Movement(mm) with analytically calculated field
220kV	Al	183.8149	202.5718
	Cu	0.0000	0.0000
300kV	Al	246.7383	383.2635
	Cu	0.0000	0.0000

400kV	Al	324.3816	528.1782
	Cu	115.857	158.3871
500kV	Al	359.9123	508.1992
	Cu	179.8820	281.1707
800kV	Al	497.2114	595.5904
	Cu	378.8287	403.5380

Similarly for Aluminium particles with CSM calculated electric field the maximum axial movement is 183.814mm and with analytically calculated field 202.5718mm for 220kV. The maximum axial movements of Aluminium particles are increasing with increase of voltage and for 800kV these maximum movements are reaching 497.2114mm and 595.5904mm for electric fields calculated with CSM and analytical methods respectively. For Copper particles, there is no axial movement for up to 300kV with and without image charge effects and for 400kV, the maximum axial movement is 115.857mm and 1243.646mm with CSM and analytically calculated fields respectively. The maximum axial movements of Copper particles are increasing with increase of voltage and for 800kV these maximum movements are reaching 378.828mm and 403.538mm for CSM and analytically calculated fields respectively. Table II represents Aluminium and Copper particle maximum axial movement for different voltages with and without image charge effects.

Fig. 3 to Fig. 6 show the radial movement patterns of aluminum and copper particles using Charge Simulation Method with and without image charge effect for power frequency voltages of 220kV and 800kV rms respectively.

IV-B. EFFECT OF PARTICLE LENGTH:

The particles movement is simulated for different particle lengths such as 8mm, 10mm, 12mm and 15mm with simulation time period of one second, particle radius 0.25mm, SF_6 gas pressure 0.45MPa and Restitution Coefficient 0.9 at 400kV and 800kV voltages.

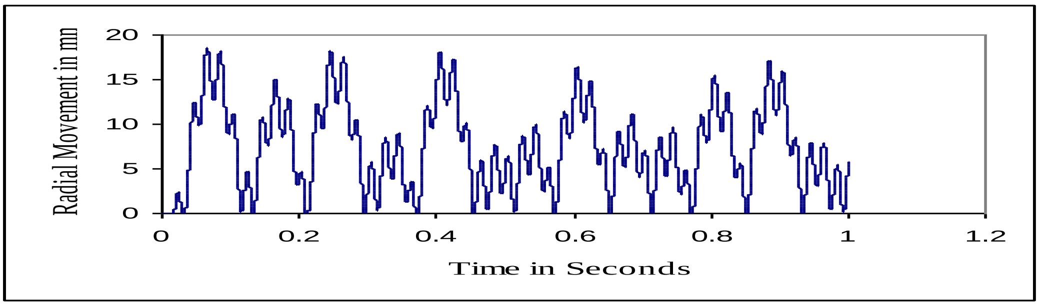

Fig.3 Al particle radial movement for 400kV with CSM calculated field

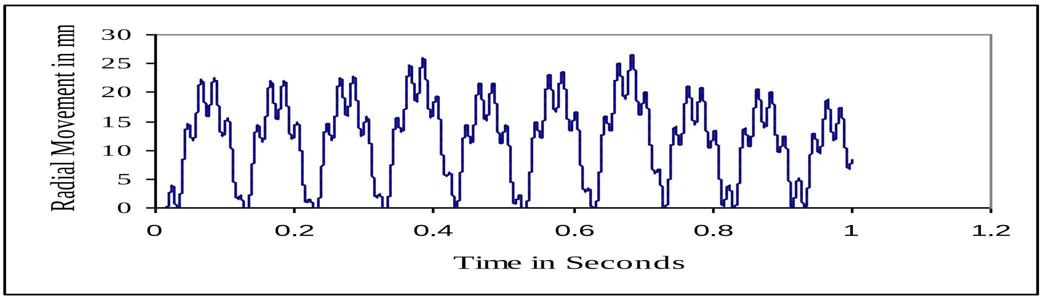

Fig.4 Al particle radial movement for 400kV with analytically calculated field

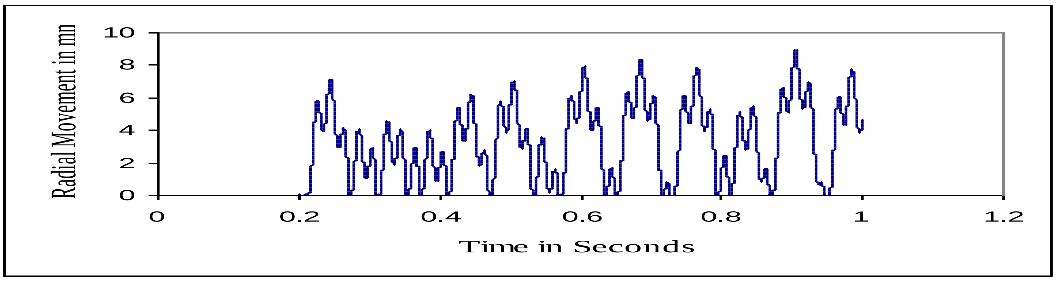

Fig. 5 Cu particle radial movement for 400kV with CSM calculated field

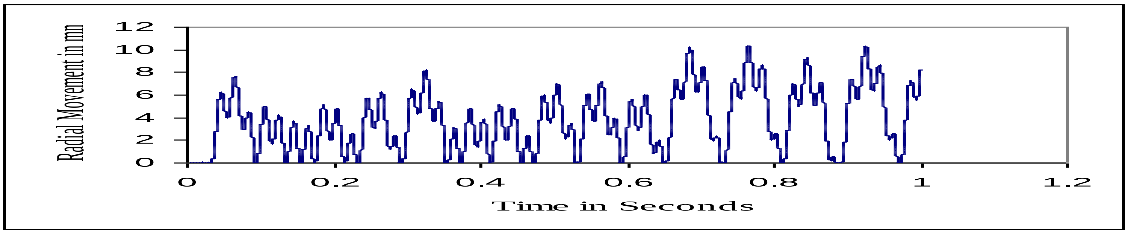

Fig.6 Cu particle radial movement for 400kV with analytically calculated field

Table III Maximum Radial Movements at different particle lengths for 400kV

Sl. No.	Particle Length (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	8	Al	13.10	11.13
		Cu	5.22	3.43
2	10	Al	17.29	13.35
		Cu	6.87	5.12
3	12	Al	20.44	15.46
		Cu	8.19	6.47
4	15	Al	25.25	20.16
		Cu	11.32	8.65

Tables III and IV show maximum radial movements with electric fields calculated by using analytical and charge simulation methods for Al and Cu particles of lengths varying from 8mm to 15mm at 400kV and 800kV voltages. Similarly, Tables V to VI represent maximum axial movements of Al and Cu particles of varying lengths at different voltages. For Aluminium particles at 400kV applied voltage the maximum radial movement with 8mm length is 13.10mm and 11.13mm with analytically calculated electric filed and CSM calculated electric field respectively. These movements are increasing with increase of particle length and for 15mm particle length the maximum radial movements are 25.25mm and 20.16mm with analytical and CSM calculated electric fields respectively. Similarly for copper particles of 8mm length the maximum radial movements are 5.22mm and 3.43mm with analytical and CSM calculated electric fields respectively. These radial movements of copper particles are also increasing with increase of particle length and reaching maximum movements of 11.32mm and 8.65mm with analytical and CSM calculated electric fields respectively. For Aluminium particles at 800kV applied voltage the maximum radial movement with 8mm length is 18.73mm and 15.47mm with analytically calculated electric filed and CSM calculated electric field respectively. These movements are increasing with increase of particle length and for 15mm particle length the maximum radial movements are 27.62mm and 26.93mm with analytical and CSM calculated electric fields respectively. Similarly for copper particles of 8mm length the maximum radial movements are 8.17mm and 5.76mm with analytical and CSM calculated electric fields respectively. These radial movements of copper particles are also increasing with increase of particle length and reaching maximum movements of 11.32mm and 8.65mm with analytical and CSM calculated electric fields respectively.

The results shown in tables III and IV Al and Cu particle radial movements are increasing with increase of length of the particle. It can be also observed that maximum radial movements are relatively less when electric field is calculated using charge simulation method and relatively high when electric fields are calculated using analytical method.

Table IV Maximum Radial Movements at different particle lengths for 800kV

Sl. No.	Particle Length (mm)	Particle type	With Analytical Field (mm)	With CSM Field (mm)
1	8	Al	18.73	15.47
		Cu	8.17	5.76
2	10	Al	24.17	18.39
		Cu	11.01	7.77
3	12	Al	27.55	21.22
		Cu	13.33	9.53
4	15	Al	27.62	26.93

		Cu	16.30	12.53

Table V Maximum Axial Movements at different particle lengths for 400kV

Sl. No.	Particle Length (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	8	Al	232.47	214.23
		Cu	83.83	54.22
2	10	Al	310.27	239.47
		Cu	109.48	79.50
3	12	Al	326.42	247.33
		Cu	121.58	104.97
4	15	Al	463.97	341.24
		Cu	180.55	121.77

Table VI Maximum Axial Movements at different particle lengths for 800kV

Sl. No.	Particle Length (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	8	Al	318.16	279.37
		Cu	120.93	105.41
2	10	Al	492.06	314.42
		Cu	176.80	121.73
3	12	Al	405.62	422.55
		Cu	235.50	165.94
4	15	Al	440.87	458.07
		Cu	279.28	221.61

The axial movements of Al and Cu particles for analytical and CSM electric field calculation methods are given by tables V and VI. From the results given in these tables it can be inferred that axial movement depends on random behavior of particle and also depends on the mass, size of the particle, the solid angle is considered for every time step and applied voltage.

IV-C. EFFECT OF PARTICLE RADIUS:

Tables VII and VIII show Al and Cu particle radial movements obtained using analytical and charge simulation field calculation methods for different particles radii varying from 0.15mm to 0.35mm at 400kV and 800kV voltages in three phase Gas Insulated Busduct with simulation time period of one second, particle length 12mm, SF_6 gas pressure 0.45MPa and Restitution Coefficient 0.9. The maximum axial movements for Al and Cu particles are given in Tables IX and X with varying particle radius from 0.15mm to 0.35mm at different voltages. For Aluminium particles at 400kV applied voltage the maximum radial movement with 0.15mm radius is 32.46mm and 29.91mm with analytically calculated electric filed and CSM calculated electric field respectively. These movements are decreasing with increase of particle radius and for 0.3mm particle radius the maximum radial movements are 14.36mm and 12.14mm with analytical and CSM calculated electric fields respectively. Similarly for copper particles of 0.15mm radius the maximum radial movements are 21.61mm and 15.19mm with analytical and CSM calculated electric fields respectively. These radial movements of copper particles are also decreasing with increase of particle radius and reaching minimum movements of 5.51mm and 4.32mm with analytical and CSM calculated electric fields respectively. For Aluminium particles at 800kV applied voltage the maximum radial movement with 0.15mm radius is 40.42mm and 35.64mm with analytically calculated electric filed and CSM calculated electric field respectively. These movements are decreasing with increase of particle radius and for 0.3mm particle radius the maximum radial movements are 21.56mm and 14.88mm with analytical and CSM calculated electric fields respectively. Similarly for copper particles of 0.15mm radius the maximum radial movements are 30.38mm and 21.84mm with analytical and CSM calculated electric fields respectively. These radial movements of copper particles are also decreasing with increase of particle radius and reaching maximum movements of 9.72mm and 6.63mm with analytical and CSM calculated electric fields respectively.

Table VII Maximum Radial Movements at different particle radii for 400kV

Sl. No.	Particle Radius (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	0.15	Al	32.46	29.91
		Cu	21.61	15.19
2	0.20	Al	21.92	21.45
		Cu	12.32	9.22
3	0.25	Al	20.44	15.46
		Cu	8.19	6.47
4	0.30	Al	14.36	12.14
		Cu	5.51	4.32

Table VIII Maximum Radial Movements at different particle radii for 800kV

Sl. No.	Particle Radius (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	0.15	Al	40.42	35.64
		Cu	30.38	21.84
2	0.20	Al	35.04	27.99
		Cu	15.43	14.47
3	0.25	Al	27.55	21.22
		Cu	13.33	9.53
4	0.30	Al	21.56	14.88
		Cu	9.72	6.63

Table IX Maximum Axial Movements at different particle radii for 400kV

Sl. No.	Particle Radius (mm)	Particle Type	With Analytical Field (mm)	With CSM Field (mm)
1	0.15	Al	525.10	511.56
		Cu	385.46	248.03
2	0.20	Al	348.63	384.17
		Cu	191.91	155.75
3	0.25	Al	326.42	247.33
		Cu	121.58	104.97
4	0.30	Al	286.53	217.28
		Cu	89.38	58.63

Table X Maximum Axial Movements at different particle radii for 800kV

Sl.No.	Particle Radius (mm)	Type	With Analytical Field (mm)	With CSM Field(mm)
1	0.15	Al	595.59	497.21
		Cu	403.53	378.82
2	0.20	Al	506.61	357.19
		Cu	221.49	237.59
3	0.25	Al	405.62	422.55
		Cu	235.50	165.94
4	0.30	Al	374.76	247.77
		Cu	142.76	106.19

From the simulated results of Al and Cu particles can be observed that the maximum radial movements are decreasing with increase of particle radius. This is because of the charge acquired is proportional to the logarithmic value of radius and mass is proportional to the square of the radius. The maximum radial movements obtained with charge simulation method are relatively less and with finite element method are relatively high.

V. CONCLUSION

A mathematical model has been formulated to simulate the movement of wire like particle under the influence of electric field in 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. Maximum movement of this metallic particle increases the probability of a flashover.

The influence of increased voltage level on the motion of the metal particles is also investigated. If the calculations, as described above, are performed at a higher voltage level, the particle will lift higher from the surface and the time between bounces will increase. 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 analytical method is more than the maximum movement in electric field calculated by using charge simulation method.

Al and Cu particle radial movements are increasing with increase of length of the particle and are relatively less when electric field is calculated using charge simulation method and relatively high when electric fields are calculated using analytical method. The Al and Cu particles maximum radial movements are decreasing with increase of particle radius because of the charge acquired is proportional to the logarithmic value of radius and mass is proportional to the square of the radius. It is noted that the maximum axial movement depends on random behavior of particle, particle size, shape, solid angle is considered for every time step and applied voltage. All the above investigations have been carried out for various voltages under power frequency. The results obtained are analyzed and presented.

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