International Journal of Engineering & Technology, 7 (4.22) (2018) 259-263

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Control of Movement of Metallic Particles in a GIS

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Abstract

The analysis of motion of metallic particles in a GIB along with a control strategy is presented in this work. Metallic particle contamination is an inevitable problem that greatly impairs the performance of dielectric medium (SF_6 gas) in a GIS. This can lead to a catastrophic failure of a GIS. A CIGRE study suggests that more than twenty percent failures in a GIS are caused due to metallic particle contamination. The mathematical modeling is done for a GIB to find the electric field and movement of metallic particle in the Busduct. The movement of metallic particles depends mostly upon the local electric fields in the duct. The motion of a contaminating metal particle can be greatly decreased by coating the enclosure inner surface with a Dielectric material. The results are simulated and validated by using AM and CSM methods.

***Keywords**: Metallic Particle contamination, Electrostatic Fields, Image Charge Effect, Dielectric Coating.*

1. Introduction

A substation is one of the most important parts of an electrical power system. The ever growing demand on the power system is a problem that needs an effective and economic solution. Erection of new substations or upgrading of existing substations is required for meeting the increased load. The scarcity and cost of real estate is a major setback for any of the two said actions. There is a need for a downsizing of the existing (Air Insulated) substation technology without compromising in the reliability and operating aspects of a conventional substation.
Gas Insulated Substations are an effective solution for this problem. A GIS is similar in working to a conventional substation (AIS) in all aspects except that the size of a GIS is many times less than a conventional substation. GIS is used in both three phase and single phase system[1]. GIS have a metallic enclosure filled with SF_6 gas housing the High tension equipment inside. The Sf_6 gas has a greater Breakdown voltage than air. The breakdown voltage of sf_6 also depends upon the pressure maintained in the enclosure. European countries typically use pressures up to 3 to 4 bar due to temperature constraints. In India, SF_6 gas can be pressurized up to 8 to 11 bar. At this pressure, the breakdown voltage of SF_6 is well over 600 to 800 % the breakdown voltage of air. In addition to the better Dielectric properties of SF_6, it has excellent arc quenching properties. The arc quenching capability of SF_6 is well over 100 times that of air [2].
GIS systems are prone to various problems such as Particle Contamination in the dielectric medium, VFTOs, Gas Decomposition[3]. In the different stages of the life of a GIS, like manufacture, assembly, transportation, commissioning, operation and maintenance, there is a very high probability of metallic particles contaminating the SF_6 gas inside the enclosure[4,5]. The Dielectric strength of SF_6 gas reduces drastically because of these metal particle contaminants which leads to uneven local fields and ultimately a catastrophic failure of the GIS system. The metallic particles are generally spherical (round), and wire like (cylindrical) in nature. These particles may rest on the inner surface of the enclosure or may be able to be able to move freely inside the GIB[6]. The motion of the metal particle depends upon the electric field intensity which again depends upon many parameters like the dimensions of the GIB, the Voltages inside the Busduct etc. The motion of these metal particles in the GIB is dangerous to the GIS and there is a need to check this movement and control it in any possible way[7]. The reliability of a GIS can be maintained by the elimination of the effects due to the movement of the metallic particles. Many methods such as Adhesive coating on the inner surface of the enclosure, Dielectric coating on the Conductor and inner surface of the enclosure, low Field areas in the GIS for Particle trapping etc. can be used to decrease the effect of metallic particles. This paper presents the Dielectric coating as a viable solution. The motion of metal particles in a single phase GIS with a Dielectric coated enclosure on its inner surface has been studied in this work. In this work IEEE Standards have been considered for simulation[8]. Various coating thicknesses have been simulated and the effect is studied. The computer simulation codes for finding out the electric field and particle movement have been written in Dev-C++ and Monte Carlo simulation technique[9] has been used. The results are validated by using both Analytical and Charge simulation methods[10,11].

2. Mathematical modeling and simulation

2.1 GIB modeling

A GIB in horizontal configuration is considered in this paper. The field calculations in the GIB are carried out in various conditions like Voltage Variations and Dielectric coating thickness using Analytical method and Charge Simulation methods.

A GIB can be modeled as seen below,

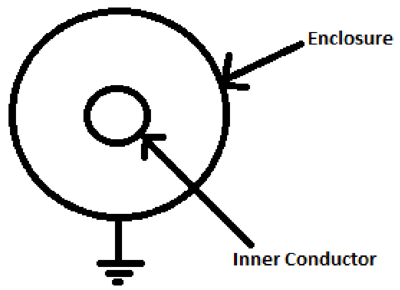

Fig.1: Cross Sectional view of a single phase GIB.

The cross sectional view of a single phase Gas Insulated Busduct is shown in Fig. 1. A grounded outer enclosure surrounds the energized conductor [4,5]. The enclosure is filled with SF_6 gas which acts as the dielectric medium.

The mechanism of charging of a metal particle in a GIB is explained by using Fig. 2.

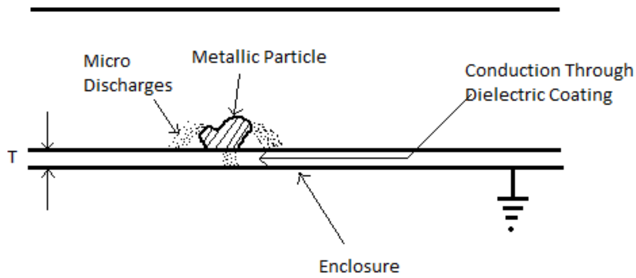

Fig. 2: Particle charge acquisition mechanism.

A contaminating metallic particle is at rest on the inner surface of the enclosure [1]. The enclosure surface is assumed to be uncoated and coated in two scenarios. The metallic particle tends to be resting until a sufficient electric field comes into existence to lift it off the enclosure. There are mainly three forces acting on the metallic particle when in motion, which are

a) Force due to gravity
b) Drag force experienced by it.
c) Electrostatic force (Actuating Force).

The movement of a contaminating metal particle in a GIB can be found out by eq (1) .

$$M\, d^2y/dt^2 = F_e - F_d - mg \quad (1)$$

Where, m = Metal particle mass
y = Particle displacement
F_e = Electrostatic force
g = acceleration due to gravity
F_d = Force due to Drag in SF_6

2.2 Electrostatic Force

The electrostatic force on the metal particle is the actuating force. When this force on the particle is greater than the sum of force of Drag experienced by the particle and its own weight, there will be a net movement of the particle. Several parameters such as the drag coefficient, particle weight, its location, viscosity of the dielectric medium (SF_6) etc. are considered.

The force due to electric field can be found out using the eq(2).

$$F_e = Q \times E \quad (2)$$

E(t) is the electric field inside the GIB. It is calculated by using Analytical and Charge simulation methods.

2.2.1 Analytical method

Electric Field calculation by using Analytical method is done by using the eq (3).

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

Where Vsinwt is the input voltage, R_e is the radius of enclosure, R_c is the radius of conductor, Y(t) is the particle position.

2.2.2 Charge Simulation Method

The following Fig. 3 shows the concepts used for the calculation of electrostatic field at a point in a GIB by using charge simulation method.

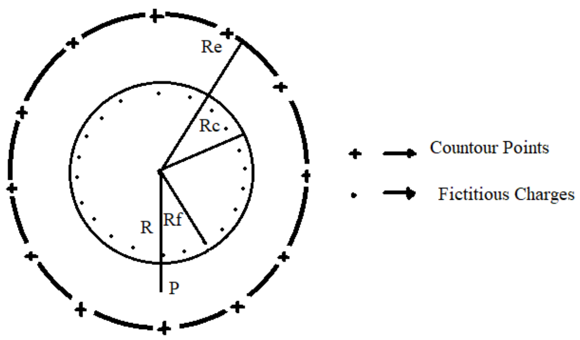

Fig. 3: Model showing charge simulation concept

The electric field at a point P(x,y) is determined by eq. (4) and (5).

$$E_x(t) = \sum_{i=1}^{n} \frac{\lambda_i}{2\pi\varepsilon} \left[\frac{x - x_i}{\sqrt[3]{(x-x_i)^2 + (y-y_i)^2}} \right] \sin \omega t \ldots\ldots (4)$$

$$E_y(t) = \sum_{i=1}^{n} \frac{\lambda_i}{2\pi\varepsilon} \left[\frac{y - y_i}{\sqrt[3]{(x-x_i)^2 + (y-y_i)^2}} \right] \sin \omega t \ldots\ldots (5)$$

Where,
$E_x(t)$ = Field component along x-axis
$E_y(t)$ = Field component along y-axis
X_i, y_i are the coordinates of i^{th} fictitious charge
λ_i denotes the line charge density
n denotes the number of fictitious charges

2.2.3 Drag Force

The drag force F_d can be calculated [9] by using the eq. (6),

$$F_d = \frac{1}{2} \rho v^2 C_d A \quad (6)$$

Where, ρ = Density of the gas,
v = Speed of the particle
A = Area of the cross section
C_d = Drag Coefficient

The equation of the motion of the particle considering all the forces at once can be written as

$$m\frac{d^2y}{dt^2} = [\frac{\pi\varepsilon_0 l^2 E(t_0)}{\ln(\frac{2l}{r})-1} \text{X} \frac{\text{V}\sin\omega t}{[\text{r}_0 - \text{y(t)}]\ln(\frac{\text{r}_0}{\text{r}_\text{i}})}] - mg - \frac{dy}{dt}\pi r[6\mu K_d(\frac{dy}{dt})$$
$$+ 2.656[\mu P_g l \frac{dy}{dt}]]............(7)$$

Eq(7) is a 2[nd] order non-linear differential equation. It can be solved by using 4[th] order R-K method [9].

Coating the inner surface of the Busduct with Dielectric material decreases the localized fields which are caused by the unevenness due to the contaminating metallic particles. The metal particle lift off field in a Dielectric coated Busduct is based on [7,10] and can be seen as the following.

$$E_{l0} = K\left[\left(1+\frac{C_c}{C_g}\right)^2 + \frac{1}{R^2\omega^2 C_g{}^2}\right]^{0.25}\left(\frac{\rho_c T}{s}\right)^{0.5} \quad ....(8)$$

3. Discussion on results

The Gas Insulated Busduct enclosure diameter is taken as 152 mm and the conductor diameter is 55 m. The gas pressure is taken as 4 bar. The Gas Insulated Substation in a horizontal configuration is considered in this work. A metallic particle, of dimensions (l=12 mm, r=0.25 mm), is therefore assumed to be resting on the inner surface of the enclosure.

The obtained results are the solution of metal particle movement equation by using 4[th] order RK method. The field calculations are done by using AM and CSM.

In the Tables 1 and 3, a comparison is given between the maximum radial movement with and without coating for Al and Cu particles by using AM and CSM methods. In Table 2 and 4, a comparison is given between the maximum axial movement with and without coating for Al and Cu particles by using AM and CSM methods.

Table 1: Maximum Radial movement of Al particle for Various voltages.

S. no	Voltages (kV)	Max. Radial Movement of Al particle (mm)			
		Analytical Method		Charge simulation Method	
		Without coating	With coating	Without coating	With coating
1	72	13.5	2.9	12.3	2.8
2	100	23.8	4.8	22	4.65
3	123	30.1	6.9	28.2	6.8
4	145	37.8	8.9	35.3	8.78
5	170	CEG	11	CEG	10
6	220	CEG	15	CEG	14.1
7	245	CEG	16	CEG	15
8	362	CEG	23	CEG	21.7
9	400	CEG	25	CEG	23.4
10	420	CEG	26	CEG	24.8

Table 2: Maximum axial movement of Al Particle for various voltages

S. no	Voltages (kV)	Max. Axial Movement of Al particle (mm)			
		Analytical Method		Charge simulation Method	
		Without coating	With coating	Without coating	With coating
1	72	2116	57	1671	51
2	100	3620	68	3575	61
3	123	5583	59.5	7286	66
4	145	6357	87.5	9181	73
5	170	6826	99	11614	87
6	220	6679	75	14765	93
7	245	6779	81	16351	99
8	362	13007	117	17784	116
9	400	40667	122	18324	120
10	420	40806	137	19187	135

Table 3: Maximum radial movement of Cu Particle for various voltages

S. no	Voltages (kV)	Max. Radial Movement of Cu particle (mm)			
		Analytical Method		Charge simulation Method	
		Without coating	With coating	Without coating	With coating
1	72	NM	NM	NM	NM
2	100	5.6	2.03	4.3	1.8
3	123	10.5	2.74	9.6	2.12
4	145	15.9	3.43	14.8	2.61
5	170	21.7	4.6	20.2	3.9
6	220	29.9	7.5	28.1	6.8
7	245	33.78	8.9	31.8	7.7
8	362	CEG	15.3	CEG	14.2
9	400	CEG	17.2	CEG	16.3
10	420	CEG	18.1	CEG	17

NM: No Movement, CEG: Crossing the Electrode Gap

Table 4: Maximum axial movement of Cu Particle for various voltages

S. no	Voltages (kV)	Max. Axial Movement of Cu particle (mm)			
		Analytical Method		Charge simulation Method	
		Without coating	With coating	Without coating	With coating
1	72	N M	N M	N M	N M
2	100	880	44	1920	42.2
3	123	10705	48.8	2254	45.4
4	145	10705	67.8	4075	58
5	170	4170	73	5267	60.6
6	220	5295	87	6313	80
7	245	5745	90	187541	84
8	362	7858	113.25	236121	92
9	400	6732	152.2	121132	151.2
10	420	6632	190.6	5946	190.41

The movement of the particle for 145 kV is 37.8 mm using AM without coating; It has been reduced to 8.9 mm with coating which is highly desirable shown in Table-1.

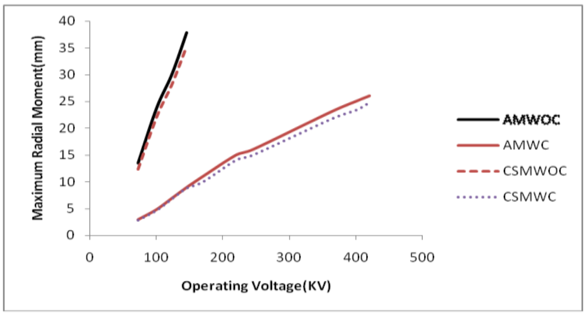

Fig. 4: Comparison of max. Radial movement of Al particle with and without Dielectric coating using AM and CSM

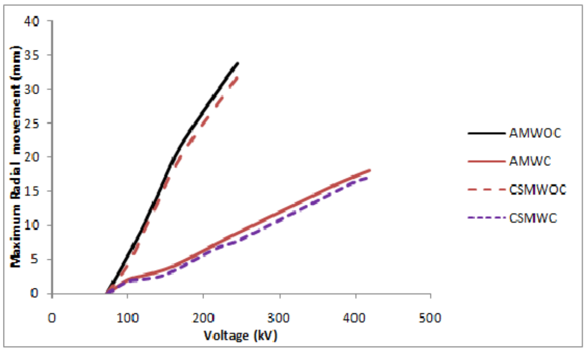

Fig.5: Comparison of max. Radial movement of Cu particle with and without Dielectric coating using AM and CSM

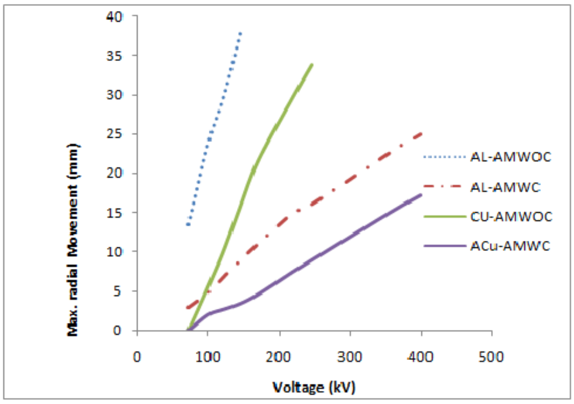

Fig.6: Comparison of max. Radial movement of Al and cu particle using AM

From Tables 1 and 3, Fig 4 and Fig.5, It can be observed that the movement of a metallic particle is reduced by using a Dielectric coating on the inner surface of the enclosure. Also it can be identified that radial movement in CSM is slightly less than that in AM. From Table 1, Table 2 and Fig.6, it is noticed that that Al has more movement than Cu because of its lighter mass.

The instantaneous radial movements of Al particle without and with a Dielectric coating are shown in Fig. 7 and Fig.8 respectively.

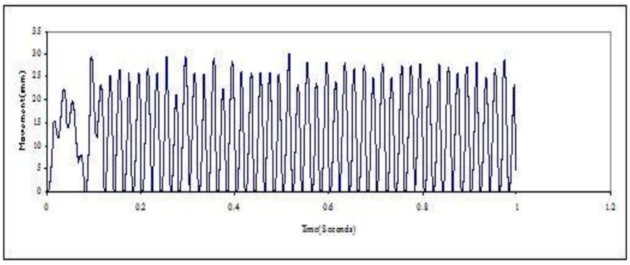

Fig.7: Al particle movement for 132 kV using Analytical method without coating

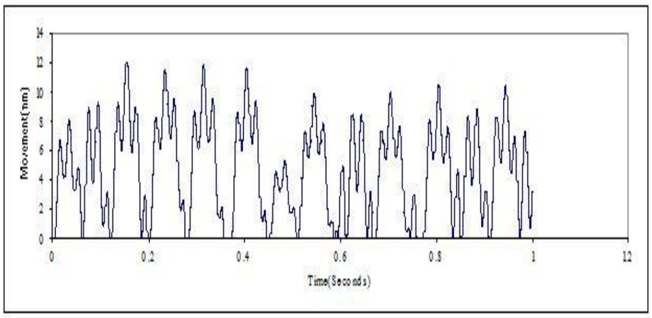

Fig.8: Movement of Al particle at 132 kV using Analytical method with coating.

It has been observed that the radial movement of Al particle with coating is less than that without coating by analysing Fig. 7 and Fig. 8.

For the variation of Dielectric thickness, the specifications of particles is taken as Length = 12mm, radius = 0.01 mm and the simulation is conducted at a voltage of 400 kV. In the Tables 5 and 6, the maximum radial and axial movements of Al and Cu particles are compared with respect to coating thickness.

Table 5: Max. Radial movement of Al and Cu particles for different coating Thicknesses using AM and CSM for 400 kV

S. no	Coating Thickness(µm)	Material	Max radial movement in mm	
			Analytical Method	Charge Simulation Method
1	100	Al	26.6	26.3
		Cu	19	18.7
2	300	Al	24.2	23.86
		Cu	15.7	15.12
3	400	Al	23	22.65
		Cu	14.4	14.15

Table 6: Max. Axial movement of Al and Cu particles for different coating Thicknesses using AM and CSM for 400 kV

S. no	Coating Thickness(µm)	Material	Max. Axial movement (mm)	
			Analytical Method	Charge Simulation Method
1	100	Al	137	134
		Cu	113	109
2	300	Al	118	115
		Cu	107	106
3	400	Al	112	111
		Cu	96.5	93

In table 5, for 100 µm thickness the motion of the particle is 26.6 mm. When the coating thickness is increased to 300 µm, the movement is decreased to 24.2. The axial movement is also decreased from 137mm to 118 mm.

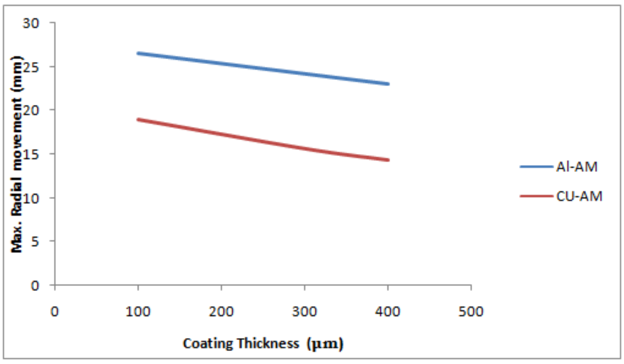

Fig.9: Comparison of max. Radial movement of Al and Cu particles with respect to coating thickness using AM

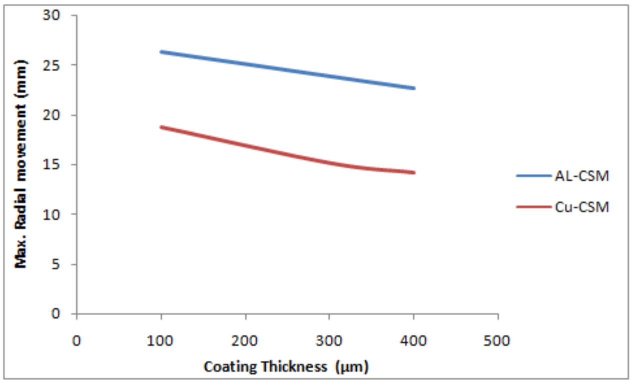

Fig.10: Comparison of max Radial movement of Al and Cu particles with respect to coating thickness using CSM.

It can be observed from Tables 5 and 6, Fig. 9 and Fig.10 that when the coating thickness is increased, the movement of the particle is decreased. This is due to the fact that when there is a thicker coating, the charge acquired by a particle is decreased which in turn decreases the net movement of the particle.

4. Conclusion

In this paper, the motion of a wire like metal particle in a GIB with a Dielectric coated surface has been studied. When the force due to electric field on the particle is more than both the gravitational force and the force due to drag, the metal particle will lift off from the enclosure. The motion of the particle increases with an increase in the electrostatic field which in turn is proportional

to the applied voltage. The motion of the metal particles in the GIB increases the probability of a flashover.
The withstand voltage of a132 kV GIS is 275 kV according to IEEE C37.122 standards. It is a best practice that the simulation need not be done for voltages greater than 275 kV which is evident from the results and IEEE standards. The movement of metallic particles is drastically reduced by using a Dielectric coating on the inner surface of the enclosure. The maximum radial movement obtained by the method CSM is slightly less than AM. Aluminium particle movement is less than that of copper particle because the mass of Al is less than the mass of Cu.

Future work

In addition to AM and CSM methods, the electric field calculations will be done by using Finite Element and Finite Difference methods. The Dielectric coating on HT conductor and Inner enclosure will be compared in future work. Different Dielectric coating materials and a comparative analysis will be carried out in future.

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