MOVEMENT OF METALLIC PARTICLE IN A SINGLE PHASE GAS INSULATED SUBSTATIONS WITH VARIOUS RANDOM SOLID ANGLES

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Abstract: *The excellent insulation properties of compressed sulphur hexafluoride are adversely affected by metallic particle contamination in practical gas insulated systems. The movement of such particles is random and the particles play a crucial role in determining the insulation behavior of GIS. The reliability of power transmission and the introduction of higher voltages to the center of big cities have been the two key features in the history of GIS. Compactness, reduction of the number of parts and simple construction on-site promote the economy of the GIS. To determine the particle movement in a single-phase Gas Insulated Bus duct (GIB) an outer enclosure of diameter 137 mm and inner conductor of diameters 40 mm are considered. Aluminum, copper and silver particles were considered to be present on enclosure surface. In order to determine the random behavior of moving particles, the calculation of movement in axial and radial directions was carried at every time step using Monte Carlo Technique. Monte Carlo simulation is also carried out by changing the random solid angle from 1 degree to 0.2 degrees in steps of 0.2 degrees. The random solid angle is decreased to take into account more smooth end profile of the particle. The simulation results have been presented and analyzed.*

Key words: *Electric Field, Gas Insulated Substations, Metallic Particles, Particle Contamination*

1. Introduction

Sulphur hexafluoride is the electric power industry's preferred gas for electrical insulation and, especially, for arc quenching current interruption equipment used in the transmission and distribution of electrical energy. Compressed Gas Insulated Substations (GIS) and Transmission Lines (CGIT) consist basically of a conductor supported on insulator inside an enclosure, which is filled with SF_6 gas.

Gas insulated sub-station systems offer a compact, cost-effective, reliable and maintenance-free alternative to the conventional air insulated sub-station systems. Their compact size offers a practical solution to vertically upgrade the existing sub-station and to meet the ever-increasing power demand in developing countries. Metal-enclosed SF_6 insulated switchgear (GIS) has already a long service experience since it was firstly introduced into the market 1968 with SF_6 also as arc quenching medium as an interesting and economical alternative to conventional air insulated substations. The use of SF_6 within the power energy supply is mainly driven by the gas - insulated switchgear.

As one is aware of the attractive features of a Gas Insulated Substation (GIS), they also suffer from certain drawbacks. One of them is the outage due to seemingly innocuous conducting particles, which accounts for nearly 50% of the GIS failures. Flash over in a GIS is, in general, associated with longer outage times and greater costs than in a conventional air insulated substation. A conducting particle 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.

Typical operating pressures for Gas Insulated system are from 240 kPa to 440 kPa. Generally the allowable design levels are used because SF_6 is very sensitive to field perturbations such as those caused by conductor surface imperfections and by conducting particle contaminants. A study of CIGRE group suggests that 20% of failure in GIS is due to the existence of various metallic contaminations in the form of loose particles. These particles may exist on the surface of support insulator, enclosure or high voltage conductor. Under the influence of high voltage, they can acquire sufficient charge and randomly move in the gap due to the variable electric field. Several authors have reported the movement of particles with reference to a few parameters.

The presence of contamination can therefore be a problem with gas-insulated substations operating at high fields. If the effects of these particles could be eliminated, then this would improve the reliability of compressed gas insulated substation. It would also offer the possibility of operating at higher fields to affect a potential reduction in the GIS size with subsequent savings in the cost of manufacture and installation. Free conducting particles are most dangerous to GIS. These free conducting particles may have any shape or size, may be spherical or filamentary (wire like) or in the form of fine dust.

Particles may be free to move or may be fixed on to the surfaces. They may be of conducting material or of insulating material. Particles of insulating materials are not so harmful as they have little effect on the insulating properties of gases. So wire like particles made of conducting material are more harmful and their effects are more pronounced at higher gas pressures. The origin of these particles may be from the manufacturing process, from mechanical vibrations or from moving parts of the system like breakers or disconnectors etc. Several authors conducted experiments on insulating particles [1-3]. However the presence of atmospheric dust containing conducting particles, especially on the cathode, reduces the breakdown voltage.

The purpose of this work is to develop techniques, which will formulate the basic equations that will govern the movement of metallic particles like aluminum, copper and silver. In this Paper the movement of particle in axial and radial directions is simulated using Monte Carlo Technique. The Random Solid angle is varied from 0.2 to 1.0 degrees in steps of 0.2 degrees and the results have been presented and analyzed. The specific work reported deals with the charge acquired by the particle due to macroscopic field at the tip of the particle, the force exerted by the field i.e., electric field on the particle, drag due to viscosity of the gas and random behavior during the movement. Wire like particles of aluminum, copper and silver of 10 mm in length and 0.25 mm as radius on a 1-phase bus duct enclosure have been considered. The movement pattern for higher voltages class has been also obtained.

2. Modeling Technique of GIB

Figure 1 shows a typical horizontal busduct comprising of an inner conductor and an outer enclosure, filled with SF_6 gas is considered for the study. A particle (wire) is assumed to be at rest at the enclosure surface, until a voltage sufficient enough to lift the particle and move in the field is applied. After acquiring an appropriate charge in the field, the particle lifts and begins to move in the direction of the field after overcoming the forces due to its own weight and drag. The simulation considers several parameters e.g.: the macroscopic field at the location of the particle, its weight, viscosity of the gas, Reynold’s number, drag coefficient and coefficient of restitution on its impact to the enclosure. During the return flight, a new charge on the particle is assigned, based on the instantaneous electric field.

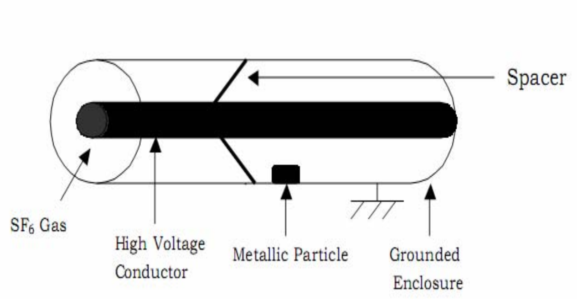

Fig. 1. Typical Single Phase Gas Insulated Bus duct

The understanding of the dynamics of a metallic particle in a coaxial electrode system is of vital importance for determining the effect of metallic contamination in a Gas Insulated System (GIS). If the motion pattern of a metallic particle is known, the probability of particle crossing a coaxial gap and causing a flashover can be estimated.

This study does not include particles that are stuck to an insulating or energized surface; since the problems with fixed conducting particles are different from those with free conducting particles. However, in order to develop appropriate mathematical models of the particle motion in a GIS, it is important to understand the charging mechanisms of metallic particles, which are in contact with electrodes. The lift-off field, which can be defined as the minimum electrical field required in the vicinity of a resting particle to make it lift from the electrode, can be estimated for a bare electrode system by making simple approximations.

For particles on bare electrodes, 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. [4]. When the electric field surrounding a particle is increased, an uncharged metallic particle resting on a bare electrode will gradually acquire a net charge. The charge accumulated on the particle is a function of the local electrical field, orientation, shape and size of the particle. When the electrostatic force exceeds the gravitational force, the particle will lift. A further increase in the applied voltage will make the charged particle move into the inter-electrode gap. This increases the probability of flashover.

The lift-off field for a particle on the surface of an electrode can be estimated by solving the following equations. The gravitational force acting on a particle of mass ‘m’ is given by

$$F_g = mg \tag{1}$$

where F_g = Gravitational force
g = acceleration due to gravity

The expression of the electrostatic force can be expressed as $F_e = KQE$; (2)

where

K is the correction factor less than unity
Q is the particle charge
E is the ambient electric field.

E(t) in a co-axial electrode system can be expressed as

$$E(t) = \frac{\hat{V}\ \mathrm{Sin}\,\omega t}{\left[r_0 - y(t)\right] l_n \left[\frac{r_0}{r_i}\right]} \tag{3}$$

where $\hat{V}\ Sin\omega t$ is the supply voltage on the inner electrode,

r_o is the enclosure radius,
r_i 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.

The motion of the particles is simulated by using the motion equation:

$$m\frac{d^2y}{dt^2} = F_e - mg - F_d \tag{4}$$

The motion equation using all forces can therefore be expressed as

$$m\ddot{y}(t) = \left[\frac{\pi \in_0 l^2 E(t_0)}{\ln(\frac{2l}{r}) - 1} \ X \ \frac{V\,\mathrm{Sin}\,\omega t}{[r_0 - y(t)]\ln(\frac{r_0}{r_i})}\right] - mg$$

$$- \ \dot{y}(t)\,\pi\, r\left(6\,\mu\, K_d\,(\dot{y}) + 2.656\,[\mu\,\rho_g\, l\,\dot{y}\ (t)]^{0.5}\right) \tag{5}$$

The above equation is a second order non-linear differential equation and in this paper, the equation is solved by using Runge-Kutta 4th Order Method.

3. Monte- Carlo Technique

The Simulation yields the particle movement in the radial direction only. However, the configuration at the tip of the particle is generally not sufficiently smooth enough to enable the movement unidirectional. This decides the movement of particle in axial direction. The randomness of movement can be adequately simulated by Monte-Carlo method [5].

In order to determine the randomness, it is assumed that the particle emanates from its original site at any angle less than ϕ, where $\phi/2$ is half of the solid angle subtended with the vertical axis. At every step of movement, a new rectangular random number is generated between 0 and 1 and modified to ϕ. The angle thus assigned, fixes the position of particle at the end of every time step, and in turn determines the axial and radial positions. The position in the next step is computed on the basis of equation of motion with new random angles as described above.

4. Results and Discussions

Table I shows the axial and radial movements of the particle in a Single Phase Gas Insulated Bus duct with Uncoated Gas Insulated System. Aluminum, Copper and Silver Particles of size 10 mm in length and 0.25 mm as radius were considered to be present on the enclosure surface. During its movement it makes several impacts with the enclosure. The highest displacement in radial direction during its upward journey is simulated to be 55.675 mm for 200 kV GIS. As the applied voltage increases the maximum radial movement also increases as given in Table I. Further calculations may reveal the limiting voltage to enable the particle to reach the high voltage conductor. The movement of copper particle was determined for 200 kV with similar parameters as above and found to have a maximum movement of 20.91 mm in radial direction. The movements are also calculated for other voltages. The movement of copper particle is also given in Table 1. It is noticed that the movement of copper particle is far less than aluminum particle of identical size. This is expected due to higher density of copper particle.

The movement of aluminum, cooper and silver particles is shown in Figures 2 to 4 for Random Solid angle of 1 degree and figures 5 to 7 show the movement pattern for various Random Solid angle of 0.5 degree. Figures 8 to 10 show the influence of voltage on the maximum height reached by the particle for different Random angles. It is observed that the nature of movement of Al, Cu, Ag particles are similar, and the aluminum particles are more influenced by the voltage than copper or silver particles due to its lighter mass. This results in the aluminum particle to acquire greater charge to mass ratio.

It is also observed that for a given particle and given voltage condition, the radial movement is the same whether or not the particle is influenced by random behavior. However, the axial movement depends on the mass, size of the particle and the solid angle considered for every time step [6]. From Table I it is seen that a lower solid angle random movement yields a lower axial movement. It therefore suggests that a more smooth ended wire will have lesser axial movement than a sharp cut wire like particle.

TABLE I

AXIAL AND RADIAL MOVEMENT OF ALUMINUM, COPPER AND SILVER PARTICLES IN A 1- PHASE UNCOATED GIB

Voltage (kV)	**Type**	**Monte- Carlo Simulation 137/40 Enclosure**			
		Axial		**Radial**	
		1 deg	**0.5 deg**	**1 deg**	**0.5 deg**
75	Al	306.5911	153.3006	11.932	11.932
	Cu	N.M	N.M	N.M	N.M
	Ag	N.M	N.M	N.M	N.M
100	Al	574.9949	287.5069	20.618	20.618
	Cu	48.8844	24.443	3.6628	3.6628
	Ag	29.2386	14.6198	2.8303	2.8303
132	Al	798.5743	399.3003	27.897	27.897
	Cu	266.4168	133.2128	10.082	10.082
	Ag	197.2358	98.6212	8.0564	8.0564
145	Al	852.6027	426.3154	32.656	32.656
	Cu	290.0764	145.043	12.191	12.191
	Ag	271.1312	135.57	10.982	10.982
200	Al	805.7321	402.8792	55.675	55.675
	Cu	329.8748	164.9428	20.91	20.91
	Ag	280.5628	140.286	15.824	15.824

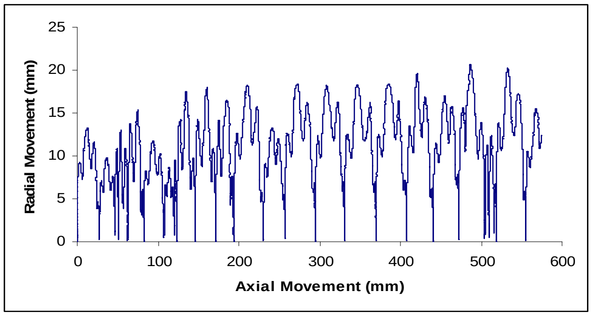

Fig 2 Axial and Radial Movement of Particle for Al / 100kV / 10mm / 0.25mm radius/ Angle 1.0

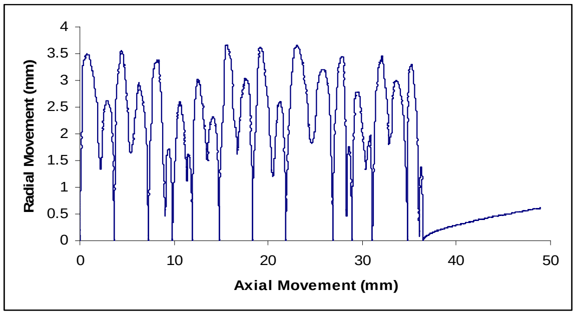

Fig 3 Axial and Radial Movement of Particle For Cu / 100kV / 10mm / 0.25mm radius/ Angle 1.0

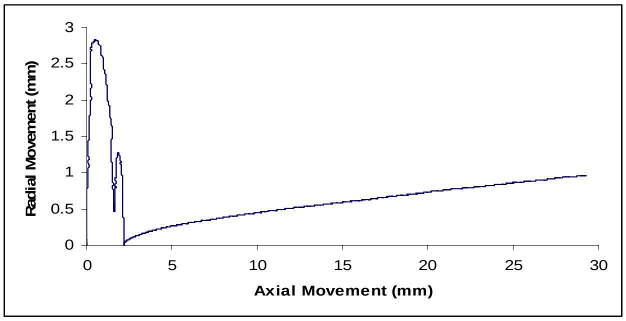

Fig 4 Axial and Radial Movement of Particle For Ag / 100kV / 10mm / 0.25mm radius/ Angle 1.0

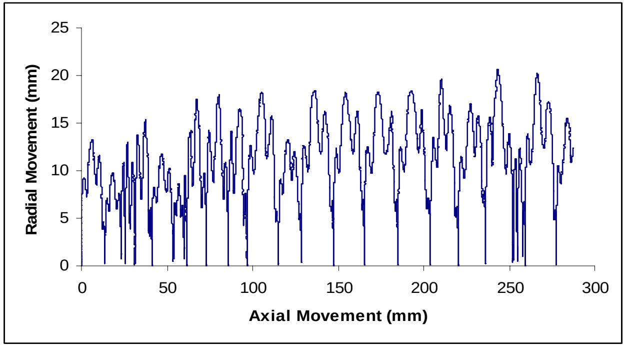

Fig 5 Axial and Radial Movement of Particle For Al / 100kV / 10mm / 0.25mm radius/ Angle 0.5

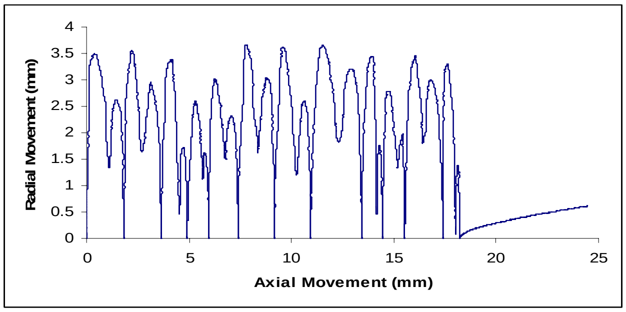

Fig 6 Axial and Radial Movement of Particle For Cu / 100kV / 10mm / 0.25mm radius/ Angle 0.5

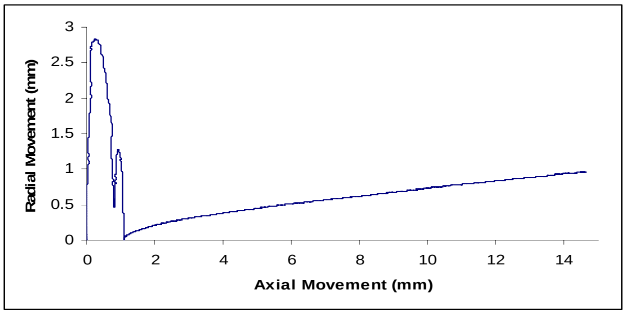

Fig 7 Axial and Radial Movement of Particle For Ag / 100kV / 10mm / 0.25mm radius/ Angle 0.5

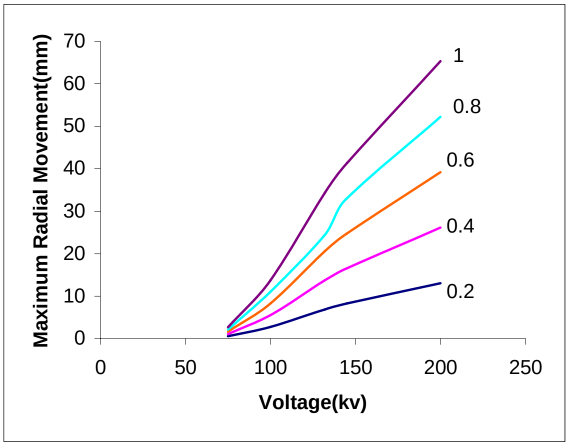

Fig.8 Influence of applied voltage on the maximum height reached by the particle for different Random angles for Al /10mm / 0.3 MPa / 0.25mm.

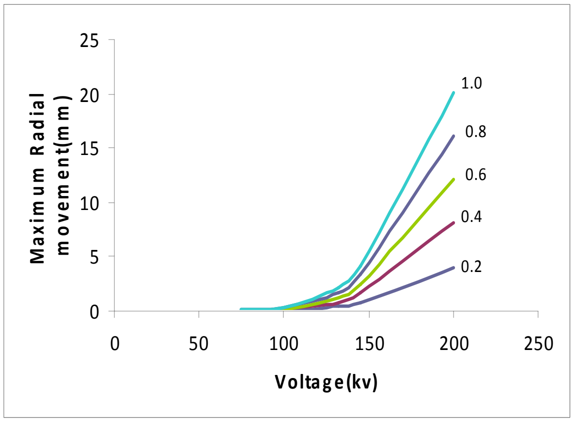

Fig.9 Influence of applied voltage on the maximum height reached by the particle for different Random angles Cu /10mm / 0.3mpa / 0.25mm.

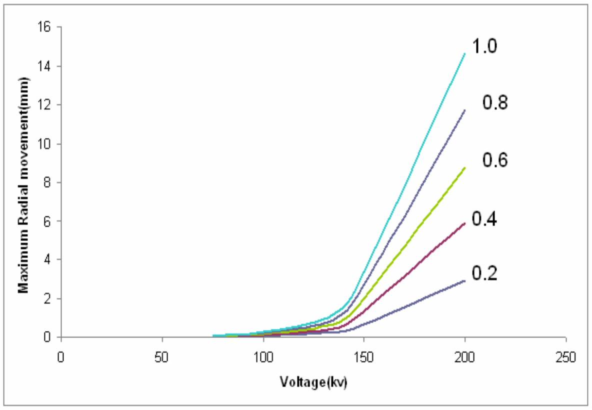

Fig. 10 Influence of applied voltage on the maximum height reached by the particle for different Random angles Ag /10mm / 0.3mpa / 0.25mm.

5. Conclusions

It has been observed that metallic particle contamination is often present in GIS and such contamination adversely affects the insulation integrity. The influence of increased voltage level on the motion of the 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. Monte Carlo simulation is carried out for calculating the behavior of particle in axial and radial directions.

The maximum movement for aluminum particle for an applied voltage of 145 kV rms in axial direction for a simulation time of 2 seconds and Monte Carlo Solid angle of 1 Degree is 852.6027 mm the same value for copper particle is 290.0764 mm and for silver particle it is 271.1312 mm. From this it can be inferred that the axial movement is strongly dependent on the random behavior of the particle. The Random Solid angle is varied from 1 degree to 0.2 degree and the axial movement and radial movement is calculated. The random solid angle is decreased to take into account more smooth end profile of the particle. From Table I it is seen that a lower solid angle random movement yields a lower axial movement. It therefore suggests that a more smooth ended wire will have lesser axial movement than a sharp cut wire like particle.

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References

1. L. G. Christophorou, J. K. Olthoff, R. J. Van Brunt, *"SF$_6$ and the Electric Power Industry"*, IEEE Electrical Insulation Magazine, DEIS, 1997, pp. 20-24.

2. M. Wohlmuth; *"Motion and Discharges of free Metallic Particles"*; 8th International Symposium on High Voltage Engineering, pp.339-342, Yokohama, Japan, August 1993.

3. H. Anis, K.D. Srivastava; *"Free Conducting particles in Compressed Gas Insulation";* "IEEE Trans. on Electrical Insulation, Vol E1-16, pp.327-338, August, 1981.

4. N.J.Felici; *“Forces et charges de petits objects en contact avec une electrode affectee d’un champ electrique”*; Revue generale de I’ electricite, pp. 1145-1160, October 1966.

5. G.V.Nagesh Kumar, J.Amarnath, B.P.Singh *“ Monte- Carlo Simulation of Particle Movement in 1- Phase and 3- Phase Gas Insulated Bus duct”* IEEE International Conference on Condition Monitoring and Diagnosis, CMD-2006, Changwon, Korea 2nd -5th April 2006.

6. G.V.Nagesh Kumar, J.Amarnath, B.P.Singh *“Random behavior of metallic particles in various designs of single phase gas insulated bus duct using Monte Carlo technique”* IEEE International Power Modulator Conference, PMC 2008, Las Vegas, Nevada, USA at the Mandalay Bay Resort & Casino on May 27-31, 2008.