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Movement of metallic particle contamination in a gas insulated busduct under dielectric coated enclosure with electromagnetic field effect

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Abstract

The purpose of coating the inside surface of gas insulated busduct (GIB) enclosure with a dielectric material reduces the deleterious effect of electrode surface roughness, impedes the development of metallic particle initiated micro discharges, increases the field required to lift particles, and reduces the charge acquired by particles. The performance of particle contaminated compressed gas systems with dielectric coated electrodes are analyzed in this paper. The equations governing the motion of the particle due to its electromagnetic field effect has been formulated to obtain the particle trajectories. Hence simulation has been carried out to study the effect of fields on the motion of the particle with and without electromagnetic field effect under dielectric coated enclosure. Particle trajectories obtained for various voltages of aluminum, copper, and silver particles of size 12 mm in length and 0.2mm as radius present on the enclosure. The simulation results have been presented and analyzed.

Keywords: Metallic particles, electric field, electromagnetic, gas Insulated busduct.

Introduction

The development of compressed gas insulated substation (GIS) and compressed gas insulated transmission line (GITL) equipment has made rapid progress (Prakash *et al.,* 1997). The electrical insulation performance of GIS/GITL systems is adversely affected by metallic particle contamination (Srivastava & Van Heeswi,1985). However, accumulated field experience indicates that sources for such contamination are mechanical abrasions, movement of conductors under load cycling, and vibration during shipment and service. These particles may be free to move in the electric field or may be fixed on the conductors, thus enhancing local surface fields. In a horizontal coaxial system with particles resting on the inside surface of the enclosure, the motion of such particles is random but the randomness depends on the coefficient of restitution and angle of incidence when approaching the coaxial conductors. The coefficient of restitutions the ratio of incident and rebound velocities and depends nonconductor surface roughness. The conducting particles can either be free to move in the GIB or they may stick to an energized electrode or to an enclosure surface. It is a fact that free conducting particles in GIB could reduce the insulation strength drastically (Anis *et al.,* 1995).

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. 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 (Kumar *et al.*, 2007).

Morcos *et al.* (2000) discussed that 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 operating at higher fields to affect a potential reduction in the GIS size with subsequent savings in the cost of manufacture and installation. Conductors in a GIS/GITL system may be coated with a dielectric material to restore some of the dielectric strength of the compressed gas, which is lost due to surface roughness and contamination by conducting particles. The improvement in the dielectric strength of the system due to coating can be attributed to several effects. Coating reduces the degree of surface roughness on conductors. Also, the high resistance of the coating impedes the development of predischarges in the gas, thus increasing the breakdown voltage (Morcos *et al.,* 2000). The electric field necessary to lift a particle resting on the inside surface of a Gibe closure is much increased due to the coating. Once a particle begins to move in the gas gap under the applied voltage, it may collide with either conductor. With coated conductors the particle will acquire a drastically reduced charge, thus the risk of breakdown initiated by a discharge is reduced significantly. Coating thickness has been varied from a few microns to several millimeters and the influence of coated electrodes on the insulation performance has been studied under ac voltages.

Particle charging

Anis *et al.* (1989) presented that the purpose of the coating is to decrease the net charge on the particle, thus making the particle less influenced by the electric field. Charging a metallic particle on the surface of a dielectric coating is attributed to two different charging mechanisms: conduction through the dielectric coating and micro discharges between the particle and the coating. Moving particles can also acquire net charge by contacting an already charged dielectric surface if the surface resistivity of the material is high enough to enable

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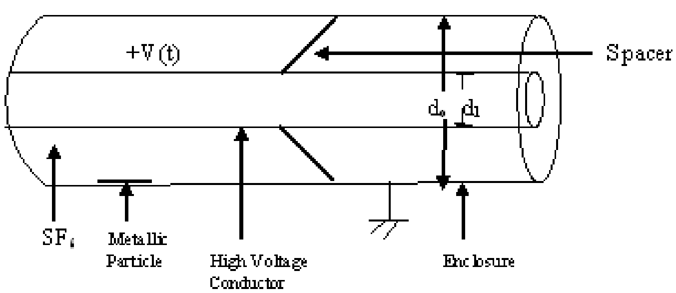
charges to be trapped on the surface. When the electric field surrounding a particle is increased, an uncharged insulated substations. It would also offer the possibility of metallic particle resting on the surface of support insulator, enclosure or a bare electrode will gradually acquire charge in proportion to the transient voltage. The charge Q accumulated on the particle is a function of the local electric field E, the shape, orientation, and size of the particle. When the electrostatic force QE on the particle exceeds the gravitational force, the particle lifts up. A further increase in the applied voltage will make the charged particle move into the inter-electrode gap. This increases the problem of flashover. A conducting particle can short-circuit a part of the insulation distance, and thereby initiate a breakdown (Laghari & Qureshi, 1981).

The work reported in this paper analyses the movement of metallic particle inside a single phase GIB (gas insulated busduct). The simulation considers the particle movement in single-phase GIB with electromagnetic field effect under coated enclosure. It is observed that the movement of particles for a given voltage level is greatly reduced while electromagnetic field effect is considered.

Fig. 1. A typical single phase gas insulated busduct.



Modeling of gas insulated busduct

Fig.1 shows a typical horizontal busduct comprising of inner conductor and outer enclosure, filled with SF_6 gas is considered for the study. A particle 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 from the enclosure surface and move in the direction of field. If the electrostatic force on the particle over comes the gravitational and frictional force on it, the particle lift-off from the rest position. During return flight, a new charge on the particle is assigned based on the instantaneous electric field. While arriving at a mathematical model of the movement of particles inside a busduct, various properties of gas particle as well as electrical properties of the system has been taken into account. Understanding 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 substations (GIS). The dynamic equation comprises the gravitational force on the particle, charge acquired by the particle, field intensity at the particle location, drag force, gas pressure, restitution co-efficient and the Reynold's number.

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

$F_g = mg$ (1)

The expression of the electrostatic force is given 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

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

Where, $\hat{V}\ \mathrm{Sin}\omega t$ 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 equation of motion for a particle can be expressed as

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

Where, m = mass of the particle, y = displacement in vertical direction

F_e = electrostatic force, F_d = drag force.

The motion equation using all forces can therefore be expressed as (5-6) becomes

$$m\ddot{y}(t) = \left[\frac{\Pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{r}\right)-1}\times V\times 29248\times 10^3\right]\left(\frac{1}{76-x}\right)\sin\omega t$$

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

Conduction through a dielectric coating:

In the case of GIS, by using a coating with a light shade on the inside of the enclosure, it is easier to detect impurities such as metallic particles or pieces of dielectric material in the system. Charging of metallic particles in contact with a coated electrode is mainly based on two deferent charge mechanisms.

i) Conduction through a dielectric coating.

ii) Micro discharges between the particle and the coating.

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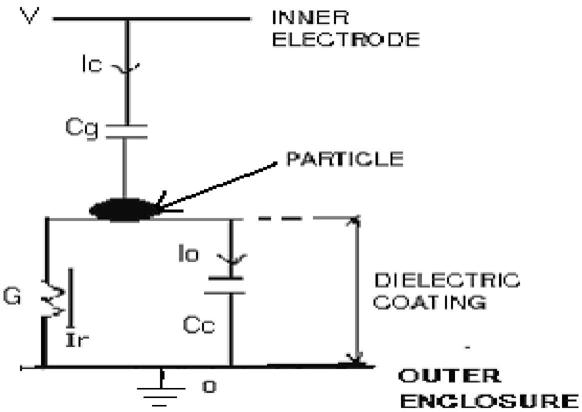
Fig. 2. Circuit model of particle charging through the dielectric coating.



Circuit model of charge mechanism of a metallic particle on dielectric coating as shown in Fig. 2.

C_g represents capacitance between the 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.

The capacitance C_c and conductance G in Fig. 3 are both dependent on the dielectric material and thickness, while the capacitance in the gas gap, Cg only depends on the gap dimensions.

The solution of the above equation for the electric field near the surface of the enclosure yields electric lift-off field (E_Lo).

$$E_{LO} = \left[\frac{mg}{\frac{K}{\omega}B(\phi)r_0 \ln\frac{r_0}{r_i}}\right]^{0.5}\left[R\left[\left(1+\frac{C_c}{C_g}\right)^2+\frac{1}{R^2\omega^2C_g^2}\right]^{0.5}\right]^{0.5}$$

$$= K\left[\left(1+\frac{C_c}{C_g}\right)^2+\frac{1}{R^2\omega^2 C_g^{\,2}}\right]^{0.25}\left(\frac{\rho_c T}{S}\right)^{0.5} \qquad (6)$$

Where, K is a constant. It can be noted that E_{LO} is approximately proportional to square root of the thickness and resistivity of the dielectric.

Modeling of single-phase isolated gib with electromagnetic field effect

Consider an electric field at a point where electric field intensity is $\overline{E}$, the force acting on unit positive charge is $\overline{F}$ N/C (or) V/m. If a charge 'Q' coulombs experiences a force is $\overline{F} = Q\overline{E}$ *Newton* (7)

Force on a moving charge Q with a velocity V in a magnetic field B is: $\overline{F} = Q(\overline{V}\times\overline{B})$ *Newton* (8)

If charge moves in a region, where the electric field and magnetic fields are simultaneously present, therefore,

$\overline{F} = Q\overline{E} + Q(\overline{V}\times\overline{B})$ or

$$\overline{F} = Q(\overline{E} + (\overline{V}\times\overline{B})) \quad Newton \qquad (9)$$

Magnetic field strength due to a long straight filament of infinite length carries a current 'I' is $\overline{H} = \frac{I}{2\pi\rho}\hat{a}_\phi \; A/m$

But the magnetic flux density, $\overline{B} = \mu H$ or $\overline{B} = \mu_0\mu_r H$

$\overline{B} = \frac{\mu_0\mu_r I}{2\pi\rho}\hat{a}_\phi$ The Lorentz force,

$$\overline{F}_{LF} = Q\overline{E} + Q(\overline{V}\times\overline{B})$$

Here we assumed as electric field intensity is static

$$\overline{V} = \frac{dy}{dt}\hat{a}_r \quad \overline{F}_{LF} = Q\overline{E} + Q(\overline{V}\times\overline{B})$$

$$\overline{F}_{LF} = \frac{\pi\varepsilon_0 \; l^2E(t_0)}{\ln\left(\frac{2l}{\gamma}\right)-1}\times\frac{V_m\sin\omega t}{[\gamma_0 - y(t)]\ln\left(\frac{\gamma_0}{\gamma_1}\right)} + \frac{\pi\varepsilon_0 \; l^2E(t_0)}{\ln\left(\frac{2l}{\gamma}\right)-1}\left[\dot{y}\hat{a}_c \times \frac{\mu I}{2\pi\rho}\right]$$

$$\overline{F}_{LF} = \frac{\pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{\gamma}\right)-1}\left[\frac{V_m\sin\omega t}{[\gamma_0 - y(t)]\ln\left(\frac{\gamma_0}{\gamma_1}\right)} + \dot{y}\frac{\mu I}{2\pi\rho}\hat{a}_\phi\right] \qquad (10)$$

Substitute the above Lorentz Force equation in the following motion equation.

$$m\frac{d^2y}{dt^2} = F_{LF} - F_d - F_{mg} \qquad (11)$$

Table1. Radial movement of aluminum, copper and silver particles with and without electromagnetic field effect under coated enclosure.

Voltage (kV)	Type	Maximum radial movement (mm)	
		Without electromagnetic field effect	With electromagnetic field effect
		coated	coated
100 kV	Al	0.774	0.854
	Cu	0.083	0.113
	Ag	0.046	0.068
145 kV	Al	1.602	1.758
	Cu	0.41	0.484
	Ag	0.322	0.373
200 kV	Al	2.721	2.95
	Cu	0.942	1.05
	Ag	0.782	0.876

Therefore,

$$m\frac{d^2y}{dt^2} = \frac{\pi\varepsilon_0 l^2 E(t_0)}{\ln\left(\frac{2l}{\gamma}\right)-1}\left[\frac{V_m\sin\omega t}{[\gamma_0 - y(t)]\ln\left(\frac{\gamma_0}{\gamma_1}\right)} + \dot{y}\frac{\mu I}{2\pi\rho}\hat{a}_\phi\right]$$

$$-\dot{y}\pi r\left[6\mu k_d(\dot{y})+2.656(\mu\rho_g l)^{0.5}(\dot{y})^{0.5}\right]-mgSin\theta \quad (12)$$

Hence the above equation (12) is a 2nd order non-linear differential equation; it can be solved by using Runge-Kutta 4th order method. The simulation results have been presented and analyzed.

Results and discussions

Table 1 shows the radial movement of the particle in a 1-phase isolated gas insulated busduct of aluminum, copper and silver particles by considering with and without electromagnetic field effect on the particles. The movement of Al, Cu and Ag particles for applied voltages field effect on the particle than without electromagnetic of 100 kV, 145 kV and 200 kV respectively are shown from Fig. 3-12. The particle is taken as 12 mm in length with 0.2 mm radius. Initially the particle is supposed to be resting at the bottom of the enclosure and positioned vertically. It has been observed in the Fig. 3 & 4, that the maximum movement of the aluminum particle is considerable increase when considering electromagnetic field effect at a given voltage of 100 kV. It has also been observed that the particle movement is greatly reduced while considering dielectric coating on the enclosure.

The movement of copper particle is also given in Table 1. It has been observed that the maximum movement of copper and silver particles is far less than the aluminum particle even of same size and applied voltage. This is due to the higher density of copper and silver particles. It is also noticed that as the voltage increases, the maximum movement of Aluminum, copper and silver particles increases significantly. Fig. 5 & 6 shows that the maximum movement of the copper particle is considerably increased in case of considering electromagnetic field effect than without electromagnetic field effect on the particle at a given voltage of 100 kV.

Fig. 7 & 8 shows that the maximum movement of the silver particle is considerably increased in case of

Fig. 3. Particle movement without electromagnetic field effect in a 1-phase GIB for 100 kV/Al/12 mm/0.2 mm radius.

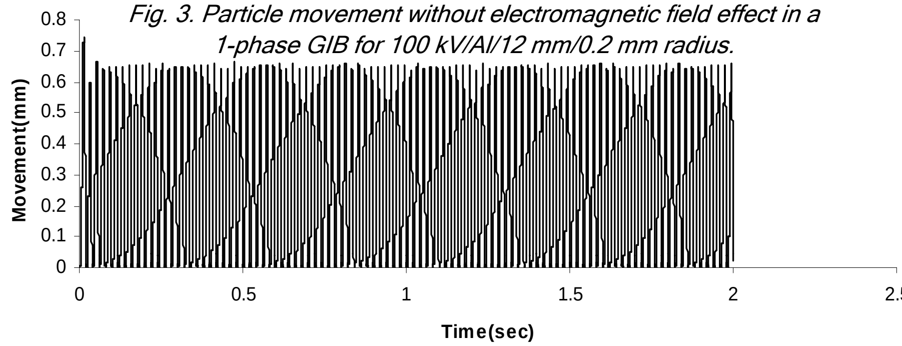


Fig. 4. Particle movement with electromagnetic field effect in a 1-phase GIB for 100 kV/Al/12 mm/0.2 mm radius.

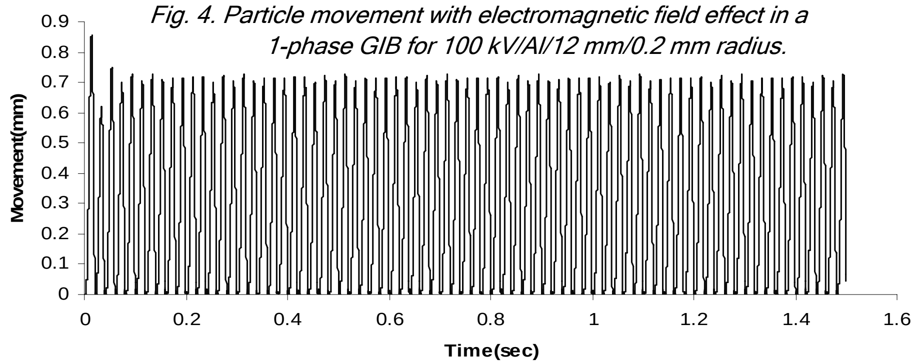


Fig. 5. Particle movement without electromagnetic field effect in a 1-phase GIB for 100 kV/Cu/12 mm/0.2 mm radius.

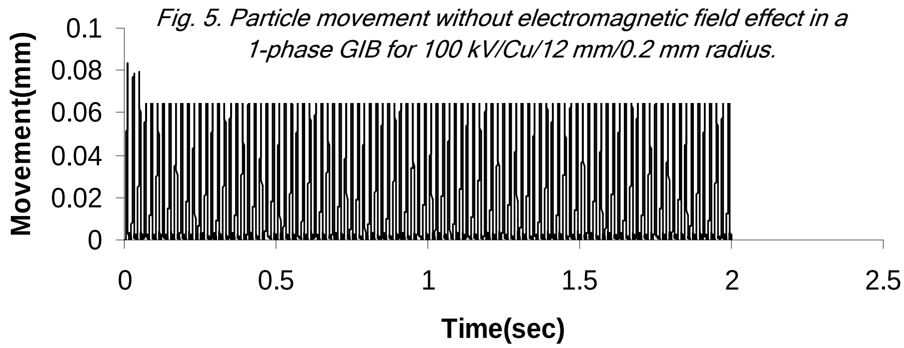
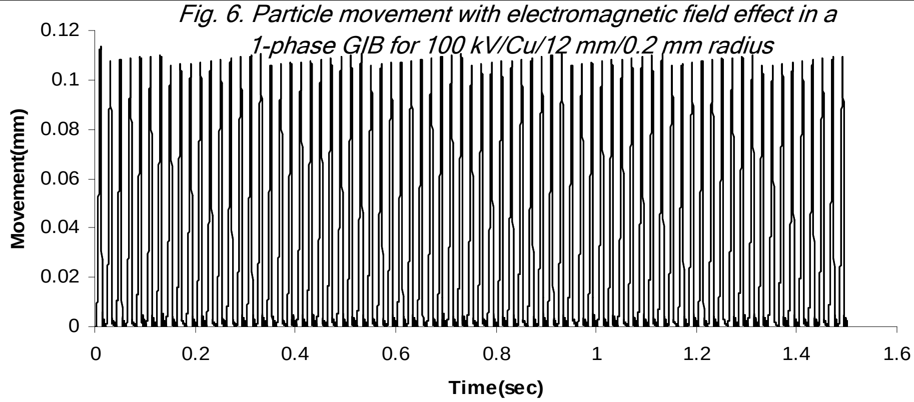


Fig. 6. Particle movement with electromagnetic field effect in a 1-phase GIB for 100 kV/Cu/12 mm/0.2 mm radius



considering electromagnetic field effect than without electromagnetic field effect on the particle at a given voltage of 100 kV.

The movement of aluminum and copper particles by considering with and without electromagnetic field effect on the particles for the voltages of 145 kV and 200 kV respectively are shown in Fig. 9-12. It has been observed that the radial movement of the particle is considerably increased when the particle is influenced by electromagnetic field effect.

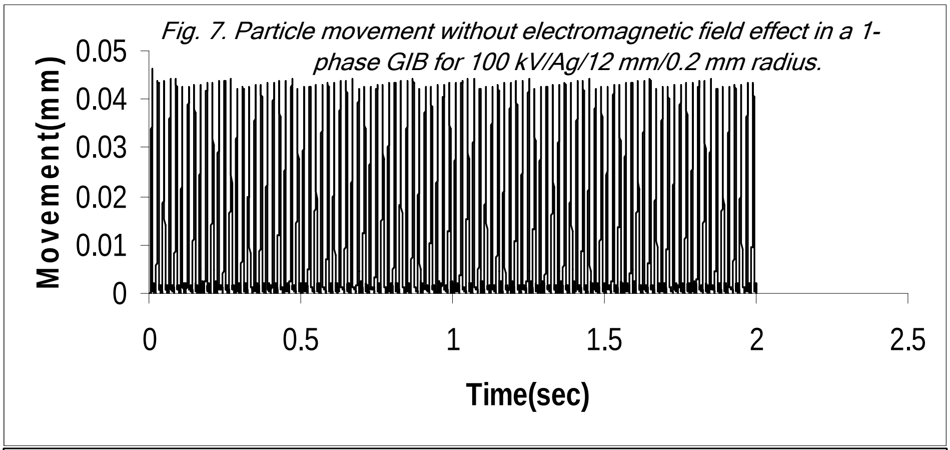


Fig. 7. Particle movement without electromagnetic field effect in a 1-phase GIB for 100 kV/Ag/12 mm/0.2 mm radius.

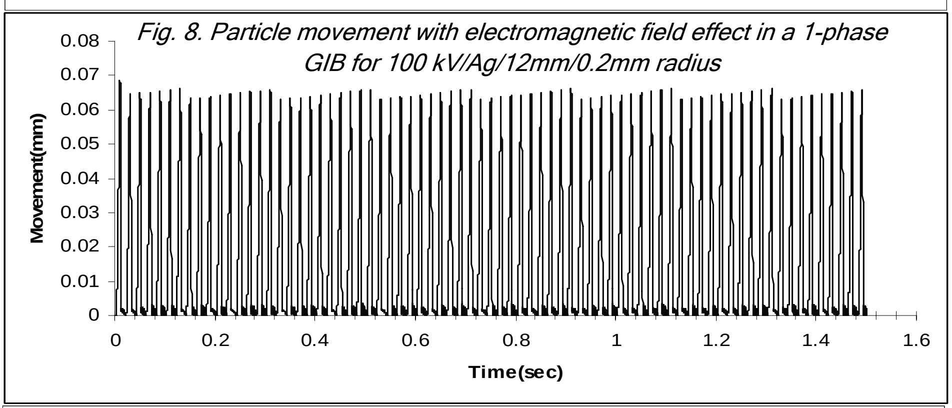


Fig. 8. Particle movement with electromagnetic field effect in a 1-phase GIB for 100 kV/Ag/12mm/0.2mm radius

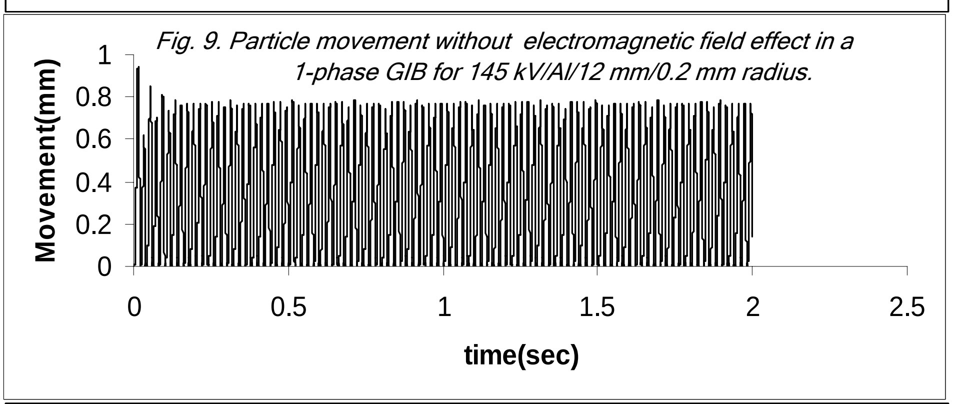


Fig. 9. Particle movement without electromagnetic field effect in a 1-phase GIB for 145 kV/Al/12 mm/0.2 mm radius.

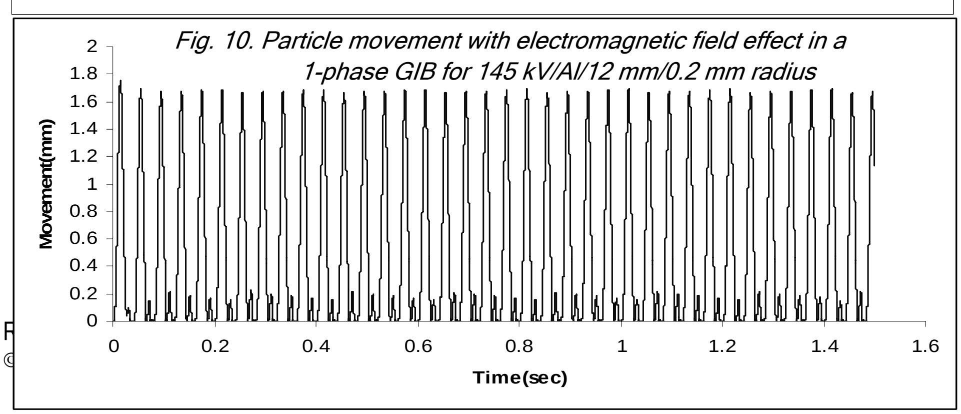


Fig. 10. Particle movement with electromagnetic field effect in a 1-phase GIB for 145 kV/Al/12 mm/0.2 mm radius

Conclusion

A mathematical model has been formulated to simulate the partial trajectories in a gas insulated busduct. The movement patterns of aluminium, copper and silver particles on coated enclosure under different voltage conditions with and without electromagnetic field on the particle have been observed for a single phase isolated conductor GIS on bare electrode system. The results obtained are presented and analyzed. There is a considerably increase in movement of the particle when electromagnetic field on the particle. The particle movement is greatly reduced while considering dielectric coating on the enclosure. All the above investigations are carried out for various voltages under power frequency.

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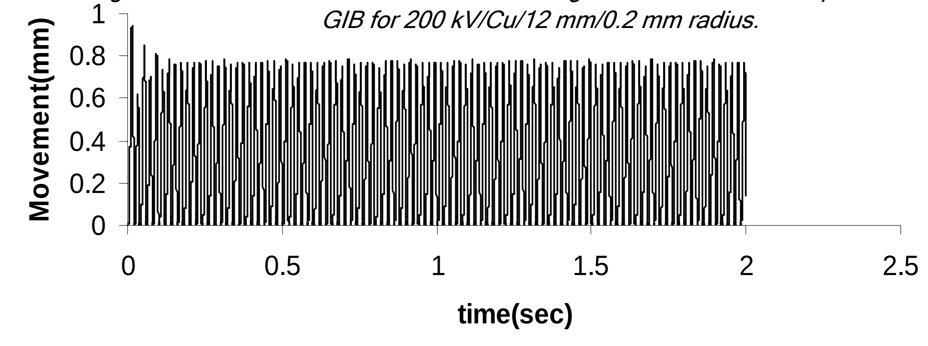

Fig. 11. Particle movement without electromagnetic field effect in a 1-phase GIB for 200 kV/Cu/12 mm/0.2 mm radius.

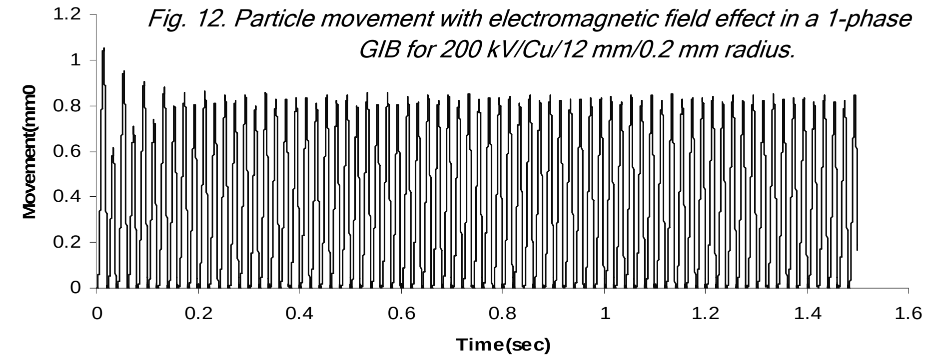

Fig. 12. Particle movement with electromagnetic field effect in a 1-phase GIB for 200 kV/Cu/12 mm/0.2 mm radius.

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