Effect of movement of multiple particles and collisions in a 3- Phase Gas Insulated Bus duct

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ABSTRACT

20% of failures in Gas Insulated Substations are due to the existence of various metallic contaminations in the form of loose particles. These particles may be free to move in the electric field or may be fixed on the conductors, thus enhancing local surface fields. In this paper a three Phase Gas Insulated Bus duct with inner diameter of each conductor 64 mm and diameter of enclosure 500 mm is considered. In this paper multiple particles i.e three particle of different sizes assumed to be rest at a position. Basic equations for the movement of three metallic particles are formulated. The motion of the three particles are simulated for different voltages using MATLAB. Effect of multiple particles for various electric fields on particle movement are analyzed and time of collisions of the particle at first time is determined for various voltages. And also the horizontal and vertical distances at which the particles collide are determined for Particles of aluminum of 10 mm in length and 0.25 mm radius, 10 mm length and 0.15 mm radius and 7 mm and 0.15 radius. The results show that the three particle collide at different points depending on the particles position , the velocity and direction of the particle changes after collisions . the max displacement of the particles without collision are compared with the max radial displacements by considering the collisions. The results show that the max displacement of particles is higher as compared with without collisions.

Keywords – multiple particles , Gas Insulated Substations, Particle Contamination, MATLAB.

I. 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 SF6 gas Basic components of the GIS bay are circuit breakers, disconnectors, earthing switches, bus ducts, current and voltage transformers, etc. The inner live parts of GIS are supported by insulators called spacers, which are made of alumina filled epoxy material. The GIS enclosure forms an electrically integrated, rounded enclosure for the entire substation. Even though SF6 exhibits very high dielectric strength, the withstand voltage of SF6 within the GIS is drastically reduced due to the presence of particles or defects like Free particles on the inner surface of the enclosure, Protrusion on the high voltage (HV) bus,

Protrusion on the inner surface of the enclosure and narrow gaps between the spacer and the electrode are due to imperfect casting and imperfect mechanical strength, The presence of contamination can therefore be a problem with gas-insulated substations operating at high fields [1]-[2].

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. wire like particles made of conducting material are more harmful and their effects are more pronounced at higher gas pressures. As given by the authors [2-5], the presence of atmospheric dust containing conducting particles, especially on the cathode, reduces the breakdown voltage

The present work deals with considering three different particles on the inner surface of the bus duct at a position, and formulating the basic equations for the movement of these metallic particles.

In this paper a Three Phase Gas Insulated Bus duct with diameter of each conductor 64mm and enclose diameter of 500mm is considered for analysis . Particles of aluminium of 10 mm in length and

0.25 mm radius, 10 mm length and 0.15 mm radius and 7 mm and 0.15 radius are considered for simulation with MATLAB

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II. MODELING OF GAS INSULATED BUS DUCT

A typical horizontal Three-phase bus duct shown in Figure (a) has been considered for the analysis. It consists of three inner conductors spaced equilaterally in a metal enclosure, filled with SF6 gas. Particles are assumed to be rest at some position on the enclosure surface, until a voltage sufficient enough to lift the particles and move in the field is applied. After acquiring an appropriate charge in the field, the particles lift and begin to move in the direction of the field after overcoming the forces due to its own weight and drag. 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[5].

Understanding the dynamics of a metallic particle is of vital importance for determining the effect of metallic contamination in a Gas Insulated System (GIS). If the motion patterns of a metallic particles are known, the probability of particle colliding in coaxial gap and causing a flashover can be estimated. The lift-off field for the particles on the surface of an electrode can be estimated by solving the motion equation.

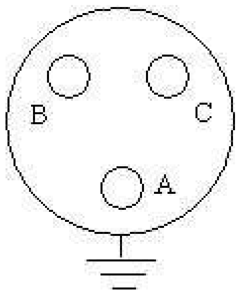


Fig. (a). Typical three phase gas insulated bus

Conducting particles in motion in an external electric field will be subjected to a collective influence of several forces. The forces are : -

-Electrostatic force (Fe)
- Gravitational force (mg)
- Drag force (Fd)

The motion equations for the three particles are given by

$$m_1 \frac{d^2 y_1}{dt^2} = F_{e1} - m_1 g - Fd_1 \text{------------}(1a)$$

$$m_2 \frac{d^2 y_2}{dt^2} = F_{e2} - m_2 g - Fd_2 \quad ----(1b) \qquad m_3 \frac{d^2 y_3}{dt^2} = F_{e3} - m_3 g - Fd_3 \quad ----(1c)$$

where m1,m2,m3 = mass of the particles
y = displacement in vertical direction
Fe = Electrostatic force
g = gravitational constant

The charges acquired by a vertical wire particles respectively in contact with a naked enclosure can be expressed as:

$$Q_1 = \frac{\pi \in_0 l_1^2 E(t0)}{\left(\ln(\frac{2l_1}{r_1}) - 1 \right)} \text{..........................} 2(a)$$

$$Q_2 = \frac{\pi \in_0 l_2^2 E(t0)}{\left(\ln(\frac{2l_2}{r_2}) - 1 \right)} \text{..........................} 2(b)$$

$$Q_3 = \frac{\pi \in_0 l_3^2 E(t0)}{\left(\ln(\frac{2l_3}{r_3}) - 1 \right)} \quad \text{......} 2(c)$$

where Q1 Q2 Q3 are the charges on the particles until the next impact with the enclosure, l1 l2 l3 are the particle length, r1 r2 r3 are the particle radii respectively , E(t0) is the ambient electrical field at t = t0. The charge carried by the particle between two impacts has been considered constant in the simulations.

The electric field in a coaxial electrode system at position of the particles can be written as:

$$E = \sqrt{E_x^2 + E_y^2} \quad \text{......} (3a)$$

$$E_x = 48.64 \times 10^3 \left[\text{Cos}0^0 \left(\frac{1}{0.125 - x} \right) + (\text{Cos}\,120^0 + \text{Cos}240^0) \left(\frac{\text{Cos}\theta_2}{R_1} \right) \right] \quad E_y = 48.64 \times 10^3 \left[\text{Sin}0^0 \left(\frac{1}{0.125 - x} \right) + (\text{Sin}\,120^0 + \text{Sin}240^0) \left(\frac{\text{Cos}\theta_2}{R_1} \right) \right]$$

where R_1 = Distance between the conductor B and particle

θ_2 = Angle between the vertical axis and R_1

x = Position of the particle within the enclosure

V_m = 200 Kv/ph V_{rms} = 245 Kv (line to line)

h = Distance between the centre of the conductor and the enclosure

r = Radius of the conductor

The electrostatic force on each particle is given by

$$F_{e1} = K\, Q_1\, E(t) \quad \text{............................} (4a)$$

$$F_{e2} = K\, Q_2\, E(t) \quad \text{............................} (4b)$$

$$F_{e3} = K\, Q_3\, E(t) \quad \text{............................} (4c)$$

Where K is a corrector and is a factor less than unity.
However, for length-to-radius ratios greater than 20 the correction factor, K, is close to unity

The drag forces are given by:

$$F_{d1} = \dot{y}\, \pi r_1 \left(6\mu K_d(\dot{y}) + 2.656 \left[\mu \rho_g\, l_1\, \dot{y} \right]^{0.5} \right) \quad \text{..........} (5a)$$

$$F_{d2} = \dot{y}\, \pi r_2 \left(6\mu K_d(\dot{y}) + 2.656 \left[\mu \rho_g\, l_2\, \dot{y} \right]^{0.5} \right) \quad \text{..........} (5b)$$

$$F_{d2} = \dot{y}\, \pi r_3 \left(6\mu K_d(\dot{y}) + 2.656 \left[\mu \rho_g\, l_2\, \dot{y} \right]^{0.5} \right) \quad \text{..........} (5c)$$

where y is the velocity of the particle, μ is the viscosity of the fluid (SF6 : 15.5_10−6kg/m_s at 200C), r1 r2 r3 are the particle radius, ρ_g is the gas density, l1 l2 l3 are the particle lengths, Kd(y) is a drag coefficient.

The influence of gas pressure on the drag force is given by empirical formula.

$$\rho_g = 7.118 + 6.332P + 0.2032P^2 \quad \text{......} (6)$$

where ρ_g= density p = Pressure of the gas and $0.1 < p < 1$mboxMPa.
The restitution coefficient for copper and aluminum particles seem to be in the range of 0.7 to 0.95:R = 0.8 implies that 80% of the incoming impulse of the particle is preserved when it leaves the enclosure.

The motion equation (1a) ,(1b),(1c) using all forces can therefore be expressed as

$$m\ddot{y}(t) = \frac{\pi \in_0 l^2 \; E(t_0)}{\ln\left(\frac{\;}{r}\right) - 1} \text{ x } 48.64 \text{ x} 10^{3} \left[\left(\frac{1}{0.125 - x}\right) + \left(\frac{\text{Cos}\theta}{R_1}\right)\right] \text{Sin}\omega t - mg$$

$$- \dot{y}(t) \; \pi r \left(6\mu K_d(\dot{y}) + 2.656 \left(\mu r_g \; l y(t)^{0.5}\right)\right)$$

In the above equation, the parameters m,l,r can be replaced by m1,l1,r1 and motion of the particle 1 can be obtained . similarly for paricles 2 and 3 motions can be obtained. The above equation is a second order non-linear differential equation and in this paper, the equation are solved using MATLAB by Runge- Kutta 4th Order Method.

III. SIMULATION OF PARTICLE MOTION

In order to determine the random behavior of moving particles, the calculation of movements in axial and radial directions was carried at every time step using rectangular random numbers. The above simulation yields the particle movement in the radial and axial directions. The random movement can be adequately simulated by Monte-Carlo method. In order to determine the randomness, it is assumed that the particle emanates from its original site at any angle less than φ, where φ/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 1and 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.

Three different particles on the inner surface of the bus duct are considered ,Particles of copper of 10 mm in length and 0.1 mm radius, 10 mm length and 0.15 mm radius and 7 mm and 0.15 radius are considered for simulation.

IV RESULTS AND DISCUSSIONS

The particle 1 has 10 mm in length and 0.1 mm radius, particle 2 has 10 mm length and 0.15 mm radius and particle 3 has 7 mm and 0.15 radius.

Table 1 shows the radial movement of the particles in a 3- Phase Gas Insulated Bus duct in Electric Field and with Monte Carlo Technique for applied voltages of 245KV ,300 kV ,400 KV and 450 KV respectively.

Table 2 shows the time at which particle collide first time Tc and Vertical height of the particle at collisions in mm velocity of the particle at just before the collision (mm /sec) . In Table 3 the velocity of the particles after collision are shown determined by calculating the angle of collisions at Tc by MATLAB .

Figure 1 to Figure 4 shows the movement patterns of aluminum particles in Electric Field and with Monte Carlo Technique for applied voltages of 245KV ,300 kV ,400 KV and 450 KV respectively

Figure 5 to Figure 8 shows the collision of particles in the bus ducts. It is observed that the three particle are started at same position and probability of collision at different points also shown in figures 5 to 8. It is seen that as the voltage varies from 245 KV to 450 KV maximum radial movement also varies as shown in Table1 and also the particles collide at different intervals. The collisions of the particles for the first time both time and height of collision also shown in Table 2. At this point of collisions (from fig 5 to 8) the particle moves randomly and its velocity and direction also changes which gives the actual maximum radial displacement would be more than the maximum radial displacement when no collision takes place.

The axial movements of particles and collision points are shown in figures 9 to 12 for the applied voltages of 245 KV,300 KV,400 KV and 450 KV respectively.

The vertical velocity and angle of collision of the particles are calculated by simulation results for different voltages 245 KV,300 kv,400 kv,450 KV respectively by knowing angle of collisions , the velocity of the particles 1, 2 and 3 after collisions are calculated as given in Appendix

In the table 3 ,the velocity of the particles just the instant after collision for different voltages is given. It is seen from the table 2 that the velocity of the particles 1 and 3 (Blue and red colours in the plot) are abruptly changes its velocity after collision. If the particles continue to move with its new velocity the maximum height of the particle would be more than that when particles are considered individually without collision as given in Table 4.

In Table 4 , it is shown that the maximum expected radial displacements of the particles after collision. For the particle 3 its expected radial displacements for 245 KV and 450 KV are almost 1.5 time as that when no collisions take place.

Table:1 Radial movement of aluminum particles with Monte-Carlo technique for various voltages.

Voltage KV	Max. Radial Movement of particle 1 (mm)	Max. Radial Movement of particle 2 (mm)	Max. Radial Movement of particle 3 (mm)
245	19.4833	8.3148	4.5726
300	27.9816	14.1787	9.7452
400	46.1633	29.1179	18.4368
450	50.9153	35.9145	29.6436

Table:2 height and time of particle collisions and velocities of the particles at just before the collision for various voltages.

Voltage KV	Time at which particle collide first time Tc (sec)	Vertical height of the particle at collisions (mm)			Velocity of the particle at just before the collision (mm /sec)		
		Particle1 (blue)	Particle2 (green)	Particle3 (Red)	Particle1 (blue)	Particle2 (green)	Particle3 (Red)
245	0.009	2	NC	2	**499**	**296**	**264.5**
300	0.011	NC	2.56	2.56	**675.4**	**403.4**	**369.8**
400	0.013	NC	4.35	4.35	**676.2**	**4236**	**360**
450	0.015	NC	6.33	6.33	**428.4**	**253.9**	**211.2**

Table:3 height and time of particle collisions and velocities of the particles after the collision for various voltages.

Voltage KV	Time at which particle collide first time Tc (sec)	Velocity of the particle at just before the collision (mm /sec)			Velocity of the particle after the collision (mm /sec)		
		Particle 1 (blue)	Particle2 (green)	Particle3 (Red)	Particle1 (blue)	Particle2 (green)	Particle3 (Red)
245	0.009	499	296	264.5	**212**	**NC**	**442**
300	0.011	675.4	403.4	369.8	**NC**	**325**	**408**
400	0.013	676.2	4236	360	**NC**	**371**	**434**
450	0.015	428.4	253.9	211.2	**NC**	**218**	**260**

Table 4. Max Radial displacements before and after collision.

s.no	Max Radial displacements without considring collisions			Max Radial displacements witht collisions		
Voltage KV	Max. Radial Movement of particle 1 (mm)	Max. Radial Movement of particle 2 (mm)	Max. Radial Movement of particle 3 (mm)	Max. Radial Movement of particle 1 (mm)	Max. Radial Movement of particle 2 (mm)	Max. Radial Movement of particle 3 (mm)
245	19.4833	8.3148	**4.5726**	19.4833	8.3148	**7.7**
300	27.9816	14.1787	**9.7452**	27.9816	14.1787	**10.77**
400	46.1633	29.1179	**18.4368**	46.1633	29.1179	**22.22**
450	50.9153	35.9145	**29.6436**	50.9153	35.9145	**36.5**

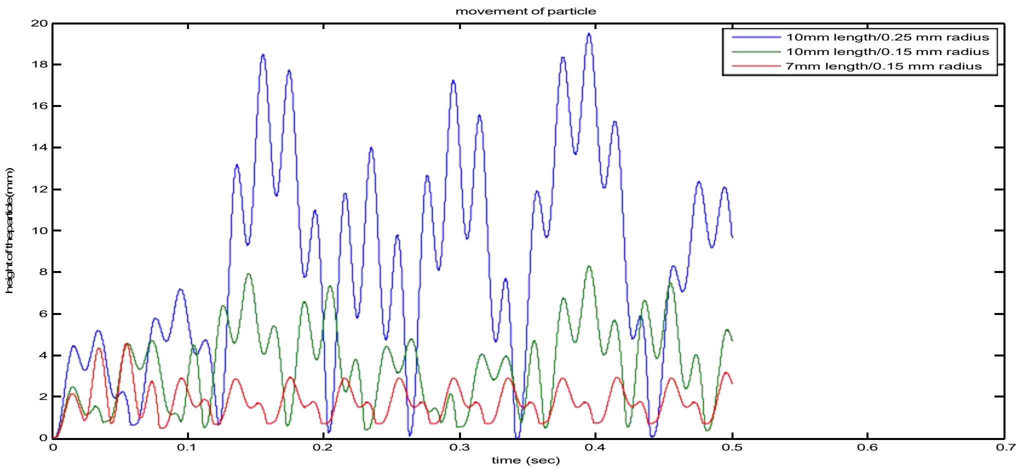


Figure:1 Radial Movement for Al/ 245 KV / 64mm - 500mm Enclosure

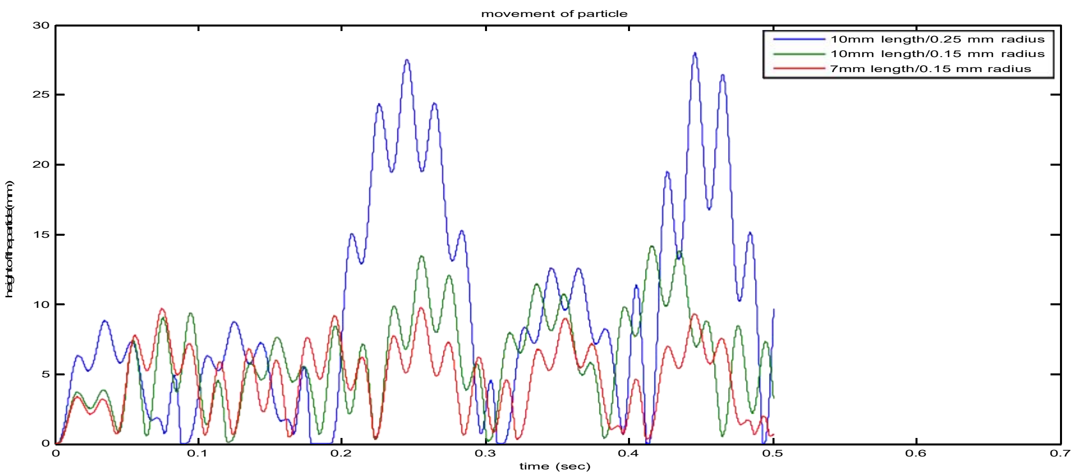


Figure:2 Radial Movement for Al/ 300 KV / 64mm - 500mm Enclosure

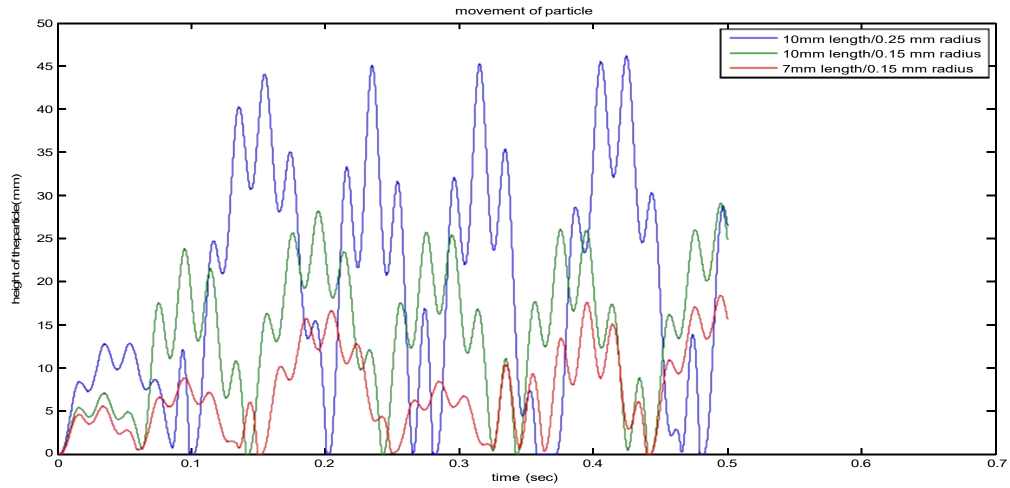


Figure:3 Radial Movement for Al/ 400 KV / 64mm - 500mm Enclosure

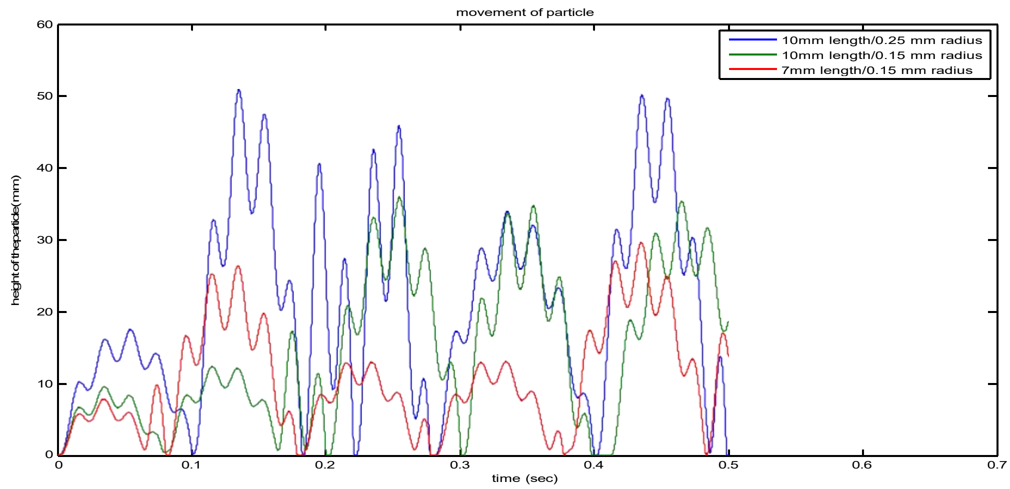


Figure:4 Radial Movement for Al/ 450 KV / 64mm - 500mm Enclosure

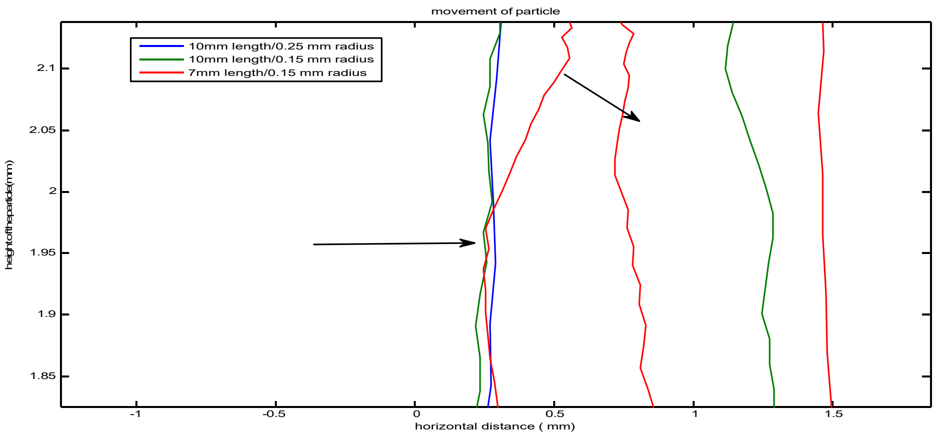


Figure:5 Particles collision for Al/ 245 KV / 64mm - 500mm Enclosure

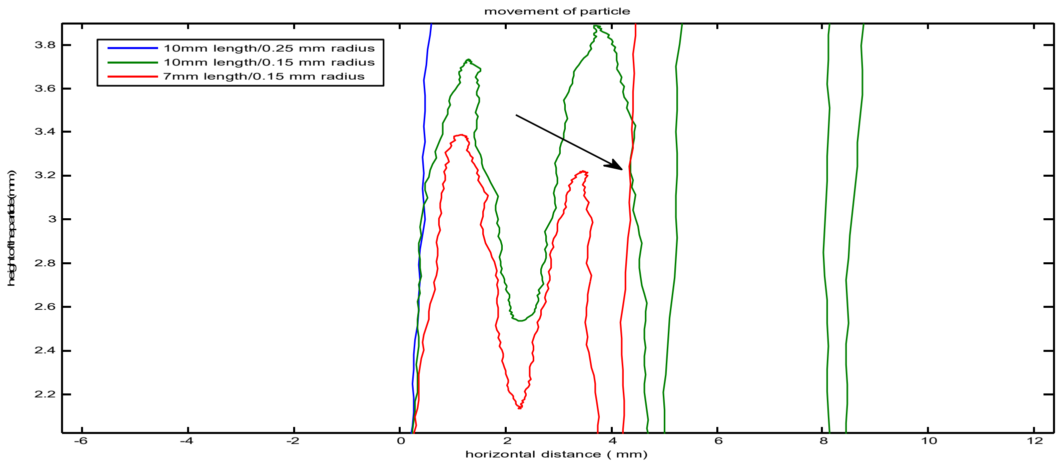


Figure:6 Particles collision for Al/ 300 KV / 64mm - 500mm Enclosure

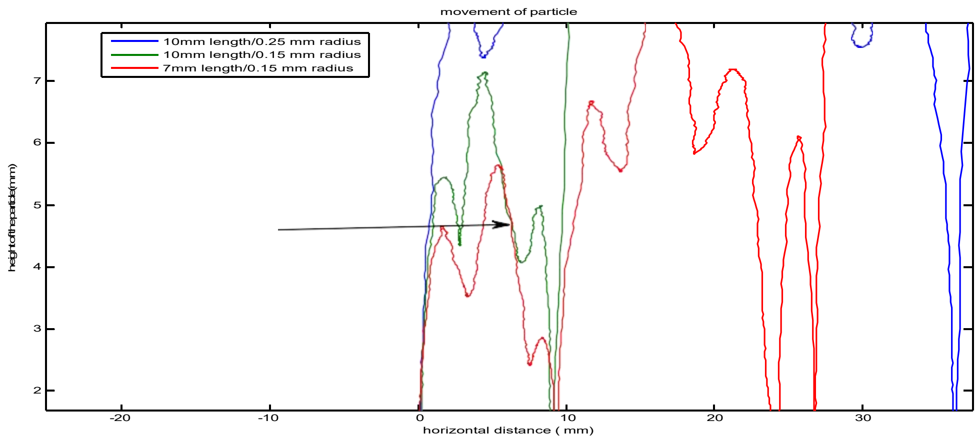


Figure:7 Particle collisiont for Al/ 400 KV / 64mm - 500mm Enclosure

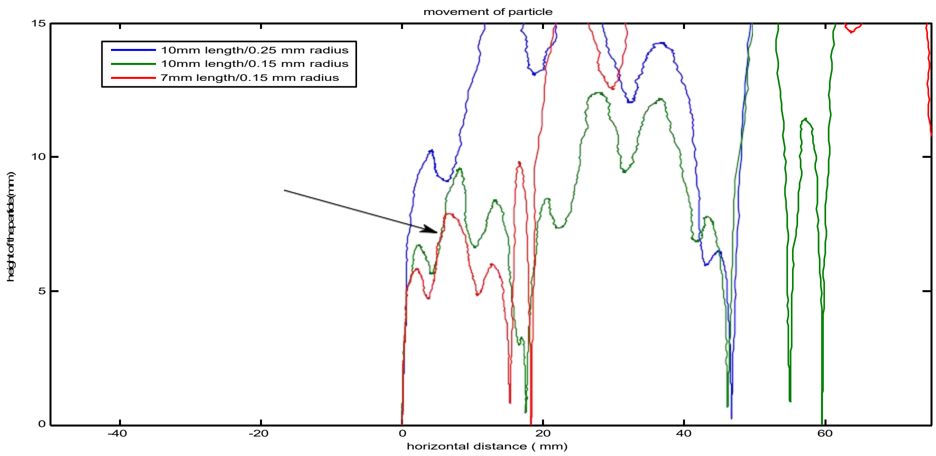
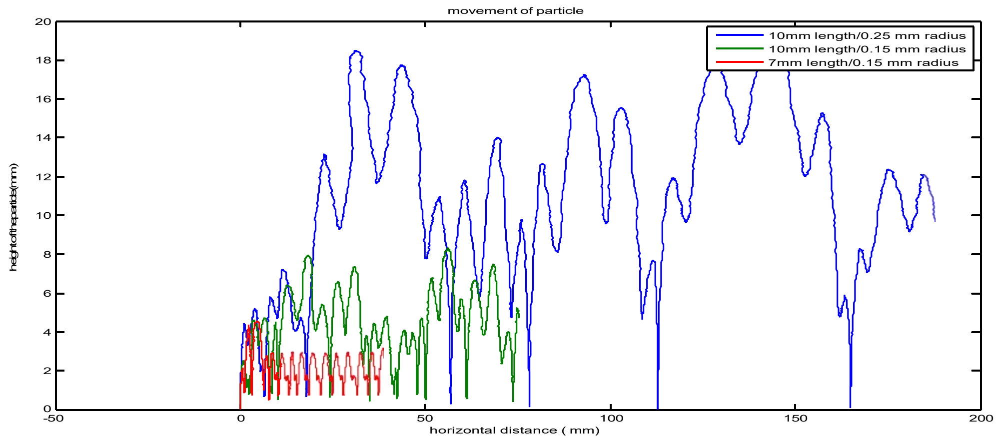


Figure:8 Particle collisiont for Al/ 450 KV / 64mm - 500mm Enclosure



. Figure:9 Axial Movement for Al/ 245 KV / 64mm - 500mm Enclosure

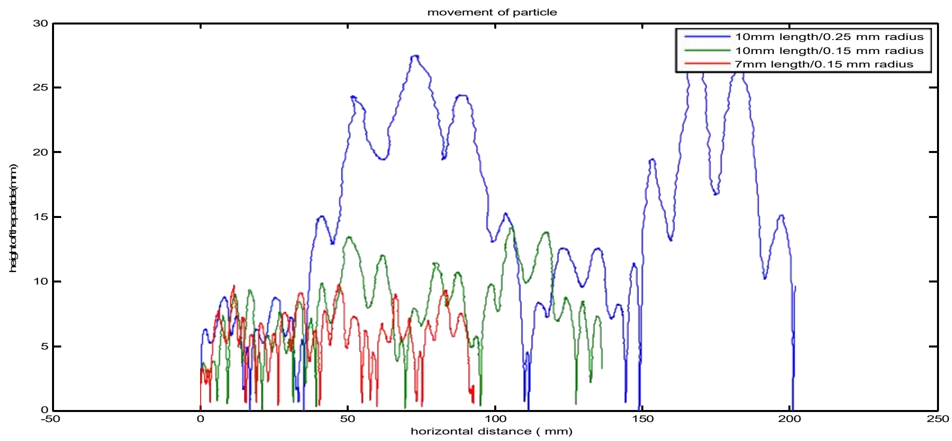


Figure:10 Axial Movement for Al/ 300 KV / 64mm - 500mm Enclosure

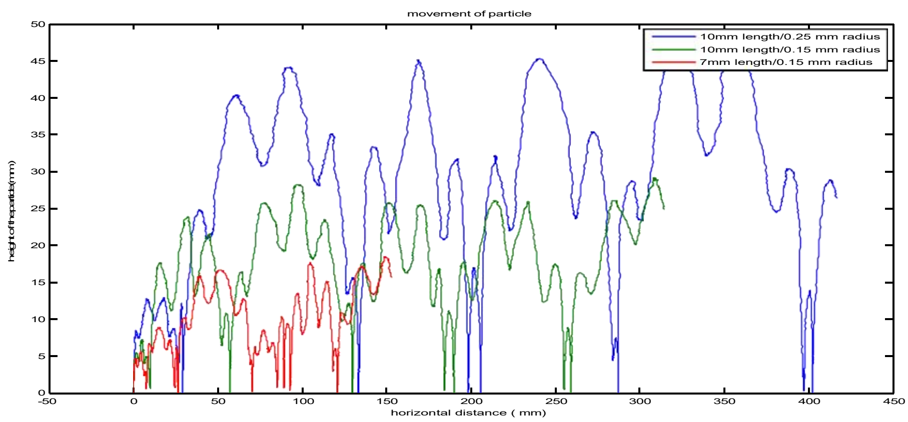


Figure:11 Axial Movement for Al/ 400 KV / 64mm - 500mm Enclosure

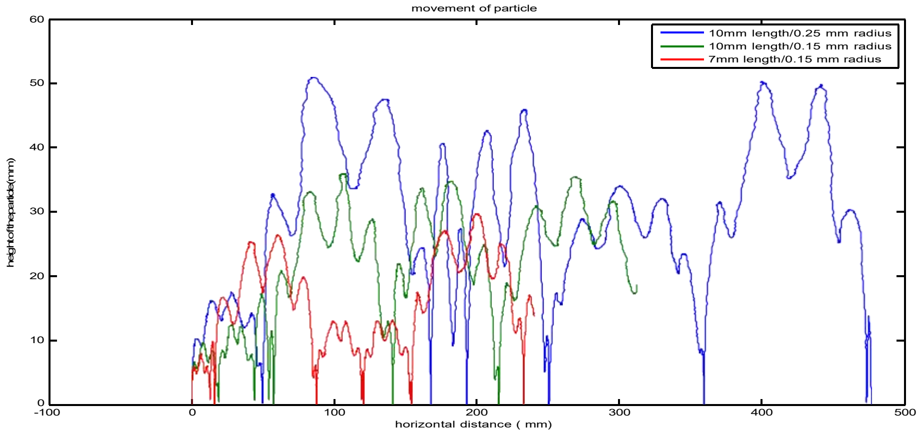


Figure:12 Axial Movement for Al/ 450 KV / 64mm - 500mm Enclosure

V Conclusion

It is shown that the probability of a flashover occurs at smaller size of the particle and at higher voltages but due to the particle collisions particles move randomly and its velocity and direction also changes which leads to flash over even at low voltages. If the calculations, as described above, are performed at a different voltage levels by considering a single particle at a time as no collisions takes place, max height of the particle and chances of flash over would be low. The results obtained from the calculations show that additional information about the particles collision and time at which first time collision takes place should be considered to estimate the flash over chances. However the collision of the particles in the gap will increase the chances of flashover.

Appendix

Two- dimensional Collision of particles

Consider two particles, denoted by subscripts 1 and 2. Let m_1 and m_2 be the masses, v_1 and v_2 the velocities before collision. For the case of two colliding bodies in two dimensions, the overall velocity of each body must be split into two perpendicular velocities: one tangent to the common normal surfaces of the colliding bodies at the point of contact, the other along the line of collision. Since the collision only imparts force along the line of collision, the velocities that are tangent to the point of collision do not change. The final velocities can then be calculated from the two new component velocities and will depend on the point of collision.

In a center of momentum frame at any time the velocities of the two bodies are in opposite directions, with magnitudes inversely proportional to the masses. In an elastic collision these magnitudes do not change. The directions may change depending on the shapes of the bodies and the point of impact.

Assuming that the second particle is at rest before the collision, the angles of deflection of the two particles, ϑ_1 and ϑ_2, are related to the angle of deflection θ in the system of the center of mass by

$$\tan\vartheta_1 = \frac{m_2 \sin\theta}{m_1 + m_2\cos\theta}, \qquad \vartheta_2 = \frac{\pi - \theta}{2}.$$

The velocities of the particles after the collision are:

$$v_1' = v_1\frac{\sqrt{m_1^2 + m_2^2 + 2m_1m_2\cos\theta}}{m_1 + m_2}, \qquad v_2' = v_1\frac{2m_1}{m_1 + m_2}\sin\frac{\theta}{2}.$$

The final x and y velocities of the first ball can be calculated as:

$$v'_{1x} = \frac{v_1 \cos(\theta_1 - \varphi)(m_1 - m_2) + 2m_2 v_2 \cos(\theta_2 - \varphi)}{m_1 + m_2} \cos(\varphi) + v_1 \sin(\theta_1 - \varphi) \cos(\varphi - \frac{\pi}{2})$$

$$v'_{1y} = \frac{v_1 \cos(\theta_1 - \varphi)(m_1 - m_2) + 2m_2 v_2 \cos(\theta_2 - \varphi)}{m_1 + m_2} \sin(\varphi) + v_1 \sin(\theta_1 - \varphi) \sin(\varphi + \frac{\pi}{2})$$

where v_1 and v_2 are the scalar sizes of the two original speeds of the objects, m_1 and m_2 are their masses, θ_1 and $\theta_2$are their movement angles, that is, $v_{1x} = v_1 \cos\theta_1,\ v_{1y} = v_1 \sin\theta_1$(meaning moving directly down to the right is either a -45° angle, or a 315°angle), and lowercase phi (φ) is the contact angle. (To get the x and y velocities of the second ball, one needs to swap all the '1' subscripts with '2' subscripts.)

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