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Study on the Factors Affecting the Movement of Contaminating Particles in Insulating SF_6 Gas in Gas Insulated Switchgear (GIS)

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Abstract: *This paper focuses on the behavior of contaminating metallic particles in the insulating compressed Sulphurhexafluoride (SF_6) gas under impulse voltage. These particles play an important role in the reduction of the dielectric strength of the SF_6 gas and enhance the probability of breakdown occurrence. The particles location in the gap filled with the insulating SF_6 gas affects the value of breakdown voltage, therefore, the study of the particles motion in the insulating SF_6 gas is very critical. The effect of the particles shapes, dimensions, configuration of the gap, the magnitude of peak impulse voltage, and drag based on the SF_6 gas viscosity are investigated in this paper. The results show a significant variation in the particles motion with the particles shapes, dimensions, peak voltage change, and the configuration of the gap.*
Keywords: *Sulphur-hexafluoride (SF_6) gas, contaminating particles motion, Gas insulated switchgear (GIS).*

I. Introduction

SF_6 is a superior gas used as insulating medium in gas insulated systems (GISs) and gas circuit breakers (GCBs) [1, 2]. Under specified conditions, the insulating gases have contaminating conducting particle. The origin of these particles may be from the manufacturing process, mechanical vibrations, or from moving parts of the system such as circuit breakers or disconnectors etc. These particles may exist on the surface of support insulator, enclosure, or high voltage conductor. The electrostatic forces can cause the contaminating conducting particles to bounce into the high field region near the high voltage electrode; therefore a breakdown occurs making a short circuit of a part of the insulation. These contaminating conduction particles can be therefore a problem with gas insulated substations operating at high fields [3]. The presence of the metallic particles in insulating gases will dramatically reduce the dielectric strength of it. In their attempt to gain an understanding of particles-initiated breakdown in SF_6 gas, various authors studied the effects of particles shape, size, material, location and motion, gas pressure, and nature of the applied field on the breakdown voltage and on the dielectric strength performance abnormal conditions [4-7].

Radwan, et. al. [4], studied the dynamic behavior of free conducting particles in SF_6 insulated systems under switching impulse (SI) superimposed on a dc voltage. The effect of some design parameters on the particle motion was investigated. These parameters are the value of dc/switching voltage ratio, particle parameters, shape of switching voltage, and system configuration; parallel plane and coaxial cylinders. They concluded that the behavior of contaminating conducting particles in GIS when subjected to a dc bias voltage and **SI** wave is more dangerous than its behavior under pure switching impulse voltage.

Metwalli and Rahim [5] introduced a theoretical analysis of the dynamics of motion of spherical metallic particles under non-uniform fields for direct-current gas-insulated switchgear (dc GIS) and for electrostatic separators/sizers (ESS). Their results reveal that the particle exhibits several phenomena during motion depending on its initial position, radius and density, angle between the diverging plates, tilt angle of the electrode system, and frequency and amplitude of the applied voltage.

Anis and Srivastava [7] introduced analytical and numerical techniques to describe the effect of the particle charge and the magnitude of the ambient electric field on the field intensification on and near the particle surface. The techniques developed in their study enable the construction of a breakdown voltage profile which describes the instantaneous voltage required to break down the insulation as the particle moves between electrodes.

This work focuses on the movement of contaminating conducting particles in insulating SF_6 gas under the impulse voltage waveshape. The movement of these conducting particles supports the breakdown occurrence because of carrying charges and approaching to the high voltage electrode. The effect of different configuration shapes of the gap, existence of the drag forces, shape of the particles shape, dimensions, applied impulse voltages, and the atmospheric conditions will be investigated.

II. Mathematical Modeling of Particles Movement under Impulse Voltage in GIS

Contaminating particles move randomly in GIS under electric field. This movement plays a crucial role in determining the insulation behavior of the gas. The micro-discharge and, in turn, the breakdown voltage, depends on the particles shape, size, material, location and motion, gas pressure, and nature of the applied field.

A conducting particle, of spherical or wire shape placed in compressed gas insulation would move under the collective influence of the following forces as shown in Fig. 1:

- Electrostatic forces which are dependent on the local field, the charge on the particle and the local ionization activity, if any. This force may assist or oppose motion depending on the field direction and the polarity of the carried charge.
- Gravitational force, which is a function of the particle's mass and affect downward.
- Drag force, which is a function of particle velocity, gas viscosity and density and the particle's shape and dimension, and constantly opposes motion [8].

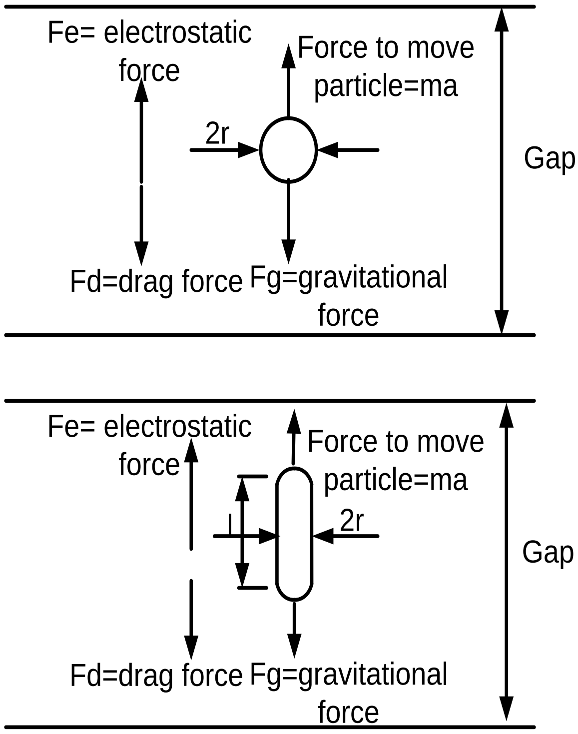

Fig. 1: Forces affecting the contaminating spherical and wire particles.

The Equation of motion of a conducting particle carrying a charge (Q) in a compressed gas is:

$$m\ddot{X} = F_e(t) - F_d \pm F_g \tag{1}$$

where, $\ddot{X}$ is the particle acceleration during motion, $F_e(t)$ is the electrostatic force ($F_e(t) = k_f.Q.E(t)$), $E(t)$ is the ambient field, k_f is a constant depending on particle shape and position, F_d is the drag force ($F_d = b_1\dot{X}$), b_1 is in general a function of particle velocity ($\dot{X}$), F_g is gravitational force (F_g= mg), m is particle mass and g is gravitational acceleration.

II.A. The Drag Force

The effect of gas pressure on particle motion can't be accounted for unless the drag force is considered. The drag forces on spherical and filamentary wire particles are examined in this section.

II.A.1. Drag force on spherical particles

Theoretically, for small relative velocities the drag force on a moving sphere (F_{d1}) is proportional to the velocity [9].

$$F_{d1} = 6\,\pi\,\mu_v\,r\,\dot{X} \tag{2}$$

where, r is the particle's radius (m), μ_v is the dynamic viscosity of the fluid in (kg/m.sec), and ($\dot{X}$) is the velocity of the particle relative to the fluid in (m/sec).
Equation (2) is valid for a Reynolds numbers (R_e) less than about 5.
where,

$$R_e = \frac{2 \ \rho_g \ r}{\mu_v} \dot{X} \tag{3}$$

where, ρ_g is the gas density (kg/m^3). The viscosity, μ_v, is mainly a function of temperature. The gas density, meanwhile, is very much dependent on pressure. Typically, for SF_6 at 20 C^o, raising the pressure from 0.1 to 1.0 MPa increases the density from about 14 to 90 (kg/m^3).
At higher Reynolds numbers, Equation (2) loses its linearity and is defined by;

$$F_{d1} = 6 \pi \mu_v r \dot{X} K_d \tag{4}$$

where, K_d, is a coefficient which increases with (R_e) in a manner that is very closely expressed by;

$$K_d = \mathrm{e}^{[0.1142 \ + \ 0.0543 \ln \mathrm{Re} \ + \ 0.051 (\ln \mathrm{Re})^2 \ ]} \quad \text{for } 5 < \mathrm{R_e} < 1000 \tag{5}$$

II.A.2. Drag force on wire particles

A filamentary wire particle shaped as a longitudinal cylinder and hemi-spherically terminated at both ends and moving in a compressible fluid encounters two drag force components. The drag force on the two hemi-spherical ends (F_{d1}) which is equal to that on a sphere having the same radius as that of the wire and thus obeys relation (4) [4]. The second drag force on a wire particle is that on its sides and is given by [4]:

$$F_{d2} = 1.328(2\pi r\dot{X} \sqrt{\dot{X} \ \mu_v \rho_g L}) \tag{6}$$

where, L is the height of semi-ellipsoidal wire particle. Therefore, the total drag force is given by,

$$F_d = F_{d1} + F_{d2} \tag{7}$$

Therefore,

$$F_d = \dot{X} [\pi r(6 \mu_v K_d + 2.656 \sqrt{\dot{X} \mu_v \rho_g L})] \tag{8}$$

II.B. Trace of the Particle Movement under Impulse Voltage

II.B.1. Fully accounted for Drag

The Equation of motion of a conducting particle carrying a charge (Q) in a compressed gas is given by Equation (1). The ambient field E(t) is proportional to the applied impulse voltage V(t). The latter is assumed to be of a double exponential impulse form and given as,

$$V(t) = K_P (e^{-\alpha t} - e^{-\beta t}) \tag{9}$$

Where, K_p,α and β are constants relating to the waveshape and magnitude. Therefore, E(t) can be written as,

$$E(t) = \frac{K_P}{X \ln \frac{r_o}{r_i}} (e^{-\alpha(t+t_L)} - e^{-\beta(t+t_L)}) \tag{10}$$

where, (t_L) is the lift off time, obtained by solving Equation (10) after replacing V(t) by the lifting voltage V_L. For a coaxial cylinder configuration, an equivalent particle travel distance is given by,[X ln (r_o/r_i)] where, X is the distance from center of a coaxial cylinder, r_o and r_i are the outer and inner radii of coaxial system. Equation (1) now reduces to:

$$\ddot{X} = H [e^{-\alpha(t+t_L)} - e^{-\beta(t+t_L)}] - b\dot{X} - g \tag{11}$$

where, b is the drag coefficient /mass parameter ($b=b_1/m$), for spherical particle: $b_1 = 6 \pi \mu_v r K_d$ and for wire particle:

$$b_1 = [\pi \mathrm{r} (6 \mu_\mathrm{v} \mathrm{K_d} + 2.656 \sqrt{\dot{X} \mu_\mathrm{v} \rho_\mathrm{g} \mathrm{L}})]$$

$H=K_cK_pQ/(m.r_o\ln(r_o/r_i))$, m is the particle mass[$m=\rho(4/3\pi r3+\pi r2L)$], and ρ is the density of particle material in (kg/m^3), K_p is waveshape constant and K_c is the constant depends on the gap configuration.
Integrating Equation (11) gives the particle velocity [8].

$$\dot{X} = H\left[-\frac{1}{\alpha}e^{-\alpha(t+t_L)} + \frac{1}{\beta}e^{-\beta(t+t_L)}\right] - b\dot{X} - gt + C_1 \tag{12}$$

The constant C_1 is obtained by assuming the particle to lift off from rest, i.e. X = 0 at t = 0.
Thus

$$C_1 = H\left[\frac{1}{\alpha}e^{-\alpha t_L} - \frac{1}{\beta}e^{-\beta t_L}\right]$$

Equation (12) now has the form

$$\dot{X} + bX = \Phi(t) \tag{13}$$

That solution may be shown to be

$$Xe^{\int b.dt} = \int \Phi(t)\ e^{\int b\,dt}dt + C_2 \tag{14}$$

And C_2 is obtained by letting X (t= 0) = 0 , i.e. Distance is measured from the initial position solving the above Equation in X gives,

$$X(t) = \frac{H}{\alpha(b-\alpha)}e^{-\alpha(t+t_L)} + \frac{H}{\beta(b-\beta)}e^{-\beta(t+t_L)} - g\left[\frac{t}{b} - \frac{1}{b^2}\right] + \frac{C_1}{b} + C_2 e^{-bt} \tag{15}$$

Where,

$$C_2 = \frac{H}{\alpha(b-\alpha)}e^{-\alpha t_L} - \frac{H}{\beta(b-\beta)}e^{-\beta t_L} - \frac{g}{b^2} - \frac{C_1}{b} \tag{16}$$

II.B.2. Constant drag coefficient

The solution of Equation 1 when the drag coefficient constant is as Equation 15 except the parameter K_d in Equation 5 will be 1.

II.B.3. Negligible drag

At very low pressures, or with low particle velocities, drag forces may have negligible values. In such cases the drag coefficient/mass parameter [b (sec^{-1})] may be set to zero in Equation (16). To avoid indefinite answers, substitution will have to be made after obtaining the limits of X (t), as b tends to zero. This yields the drag-free travel as,

$$X(t) = H\left[\frac{1}{\alpha^2}e^{-\alpha(t+t_L)} - \frac{1}{\beta^2}e^{-\beta(t+t_L)}\right] - \frac{gt^2}{2} + C_1 t + C_2 \tag{17}$$

Where,

$$C_2 = -H\left[\frac{1}{\alpha^2}e^{-\alpha(t_L)} - \frac{1}{\beta^2}e^{-\beta(t_L)}\right] \tag{18}$$

II.C.1. Lifting Field and Charge of a Spherical Particle

A particle resting at the bottom of an electrode will be lifted, if a sufficiently high voltage is applied, when the electrostatic force exceeds the gravitational force. Felici [6] have calculated the charge accumulated and the lifting electrostatic force on spherical particles in contact with a plane in a uniform field. A spherical conducting particle of radius r (m) lying on the bottom electrode (the outer electrode in a coaxial system) as shown in Fig. 1 and subjected to a constant ambient field (E) sustains an electrostatic force ($F_e = K_f .Q. E$) where, E is the ambient field, Q is the particle charge and K_f is a correction constant which, for a spherical particle is equal to 0.832 [7, 10]. The particle lifts off when the electrostatic force is equal to or greater than the weight of particle (m*g) as shown in Fig. 1, where, m is the particle mass and g is the gravitational acceleration. Felici demonstrated analytically that the charge acquired by the particle is given by [5, 6];

$$Q = \frac{2}{3}\pi^3 \varepsilon_o r^2 E \tag{19}$$

To calculate the lifting field and lifting charge the weight of the particle is equated to the electrostatic force as shown in Fig. 1,

$$m\,g = k_f\, Q_o E_o \tag{20}$$

For a spherical particle, the particle mass is $(m) = \frac{4}{3}\pi\, r^3 \rho$ where, ρ is the particle material density. Put m in Equation (20), hence,

$$\frac{4}{3}\,\rho g \pi\, r^3 = k_f\, Q_o\, E_o = k_f\ \left(\frac{Q_o}{E_o}\right)\ E_o^{\,2} \tag{21}$$

But from Equation (19),

$$\frac{Q_o}{E_o} = \frac{2}{3}\pi^3\, \varepsilon_o\, r^2 \tag{22}$$

Substituting Equation (22) in (21) yields,

$$E_o = 473.8\sqrt{\frac{r\rho}{k_f}} \quad kV/m \tag{23}$$

By substituting E_o into Equation (22), the accumulated charge on a spherical particle at lift off is given by;

$$Q_o = 0.95\times 10^{-4}\sqrt{r^5\rho} \tag{24}$$

II.C.2. Lifting Field and Charge of a Filamentary Wire Particle

In practical, compressed gas insulated apparatus most contaminating particles have been reported to be filamentary in shape [11-14]. A filamentary particle may be represented by a semi-ellipsoid [11, 13] for which Felici [6] had derived the carried charge (Q) and the electrostatic force when it is in contact with a plane in constant ambient field. Based on Felici’s work and recalling that filamentary particles were experimentally reported to lift off from the bottom electrode in vertical (longitudinal) direction [11], the carried charge and lifting field in this case is given by:

$$Q_o = \frac{\pi\varepsilon\ L^2 E_o}{ln\frac{2L}{r} - 1} \tag{25}$$

and

$$E_o = \left(ln\frac{2L}{r} - 1\right)\sqrt{\frac{r^2\rho\quad g}{\varepsilon\, L\left[ln\frac{2L}{r} - 0.5\right]}} \tag{26}$$

where, L is the height of semi-ellipsoidal of wire particle and r is the radius of its base.

To calculate the lifting field (E_o) and charge carried by a vertical wire particle represented by a longitudinal cylinder hemi-spherically terminated at both ends.

III. Simulation of the trajectory motion of the contaminating Particles

A computer code is constructed to simulate the trajectory of the motion of contaimanting particles using Matlab platform. Fig. 2 shows the flowchart of the Matlab code. The particle motion scenario will be as follows:

1. Insertion of system data: particle shape, gap configuration, impulse waveform shape and particle parameters such as radius, length and density.
2. Calculation the accumulated particle charge lifting electric field, lifting voltage and lifting time.
3. Consider the drag type: neglected drag, constant drag coefficient, or fully-accounted drag.
4. Calculation of the trajectory motion of the contaminating particle.

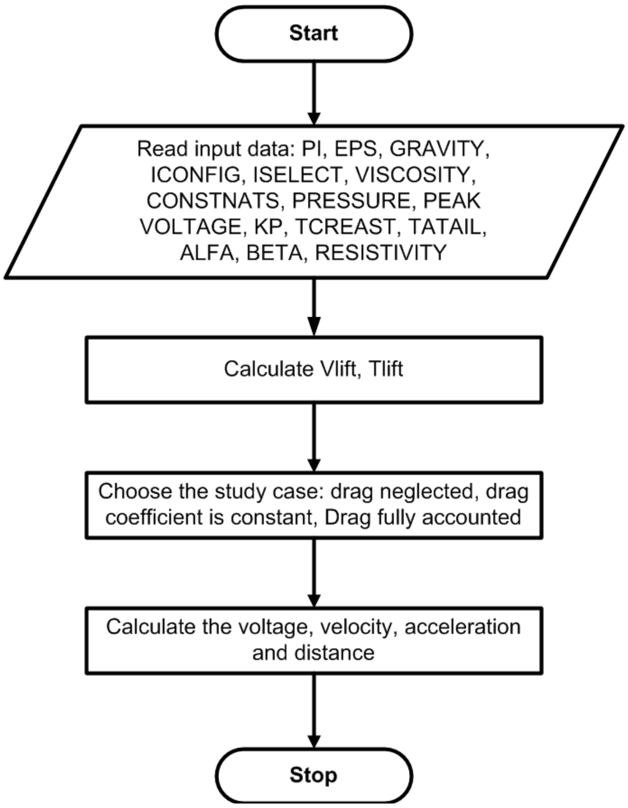

Fig. 2: Flowchart of Matlab code.

IV. Results and Discussions

The effect of different configuration shapes of the gap, existence of the drag forces, shape of the particles, shape of applied impulse voltages, the atmospheric conditions, and the particles dimensions will be investigated in this section. Figs. 3 and 4 show the effect of drag forces on the particle movement weather it is spherical or wire in shape. Figs. 3and 4 explain that the particle's movement when drag is neglected is faster than that when drag is fully accounted for. Fig. 5 illustrates the effect of the particle's shape on its movement. Fig. 5 shows also that the spherical particle is faster than the wire one at the same applied voltage.

Figs. 6 and 7 show the effect of the applied impulse voltage on the movement of a particle (spherical and filamentary wire) in GIS parallel plane gap configuration. Fig. 6 illustrates the relation between spherical particle travel and the time at different peak values of applied impulse voltage for a spherical particle contaminating a parallel plane gap. It is seen that an increase in applied impulse voltage causes an increase in electrostatic force and so an increase in the distance travel by the particle. Fig.7 shows the wire particle's travel at different peak values of applied impulse voltage. it is seen that an increase in applied impulse voltage causes an increase in electrostatic force and so an increase in the distance travel by the wire particle.

Figs. 8 and 9 illustrate the relation between the particle's travel and the time at different particle's radii in case of spherical and wire particles. It is shown that an increase in particle's radius will increase the volume of it and then increase its mass and therefore the motion is slower. But on the other hand, when the volume of the particle increases the charge accumulated on the particle will increase and may lead to a breakdown.

Fig. 10 describes the effect of wire particle length on the particle's motion. When the particle length increases then the particle will reach to a critical location faster and therefore the probability of breakdown will be higher.

Fig. 11 studies the effect of gap configuration on the particle's motion. It is seen from Figs. 11 and 12 that the particle will be faster in case of parallel plane gap rather than its motion in coaxial cylinder gap.

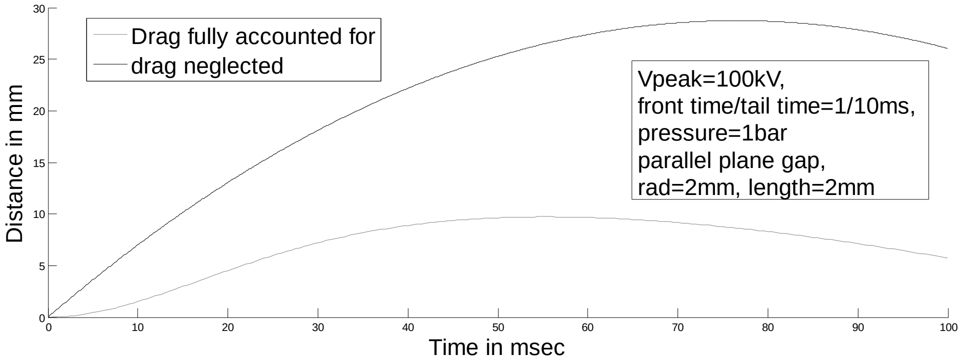

Fig .3: Effect of drag forces on the movement of contaminating wire particle.

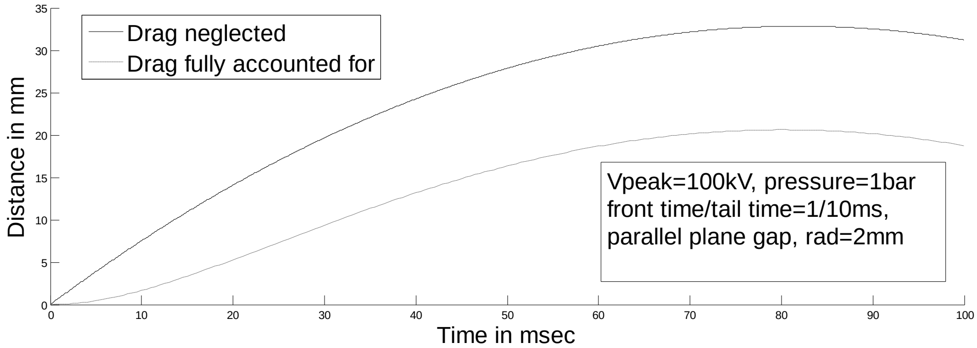

Fig. 4: Effect of drag forces on the movement of contaminating spherical particle.

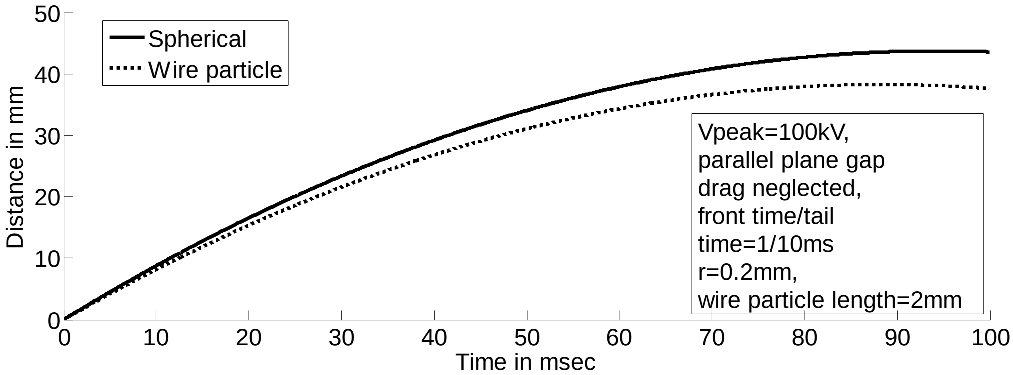

Fig. 5: Effect of particle shape on the movement.

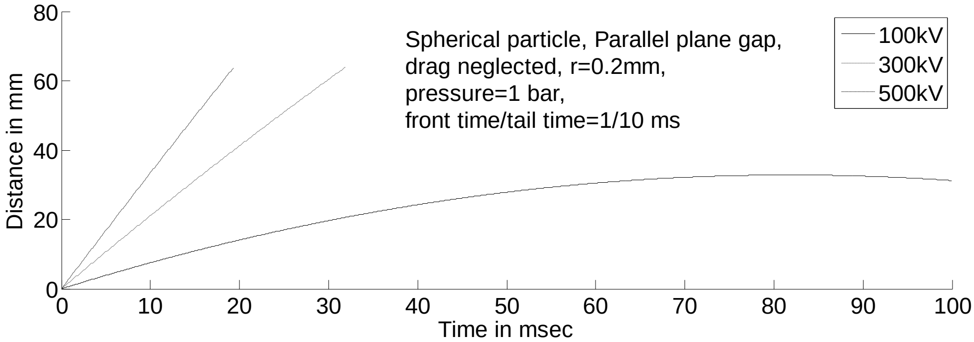

Fig. 6: Effect of applied impulse voltage on spherical particle trajectory contaminating SF_6 gas in parallel plane gap.

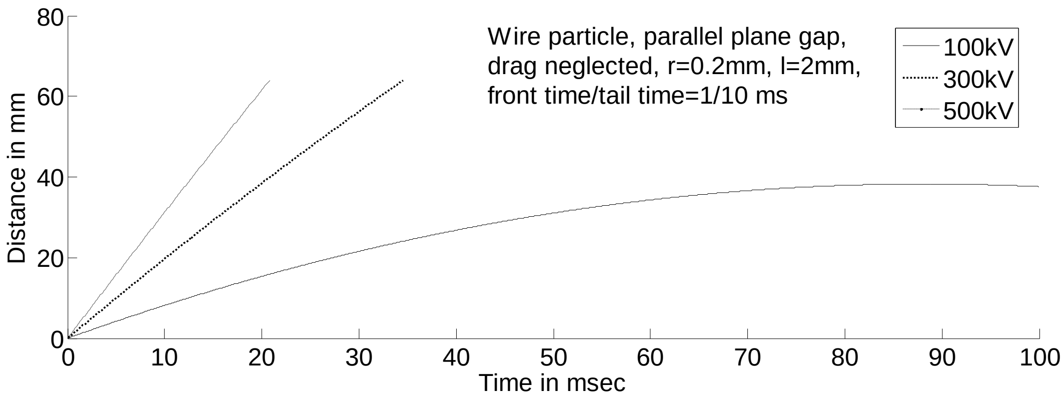

Fig. 7: Effect of the applied impulse voltage on filamentary wire particle trajectory contaminating SF_6 gas in parallel plane gap.

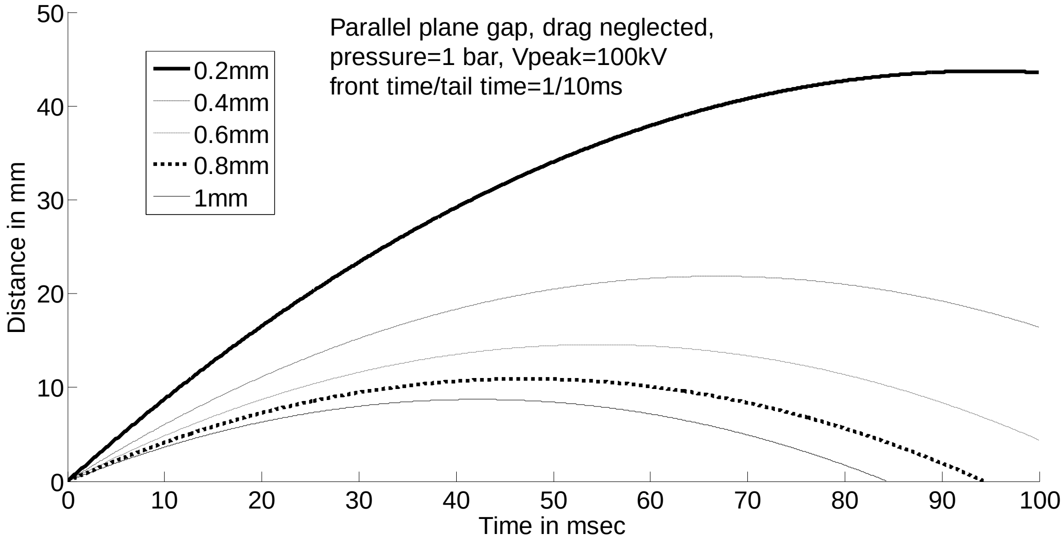

Fig. 8: Effect of spherical particle radius on the movement of it in parallel plane gap.

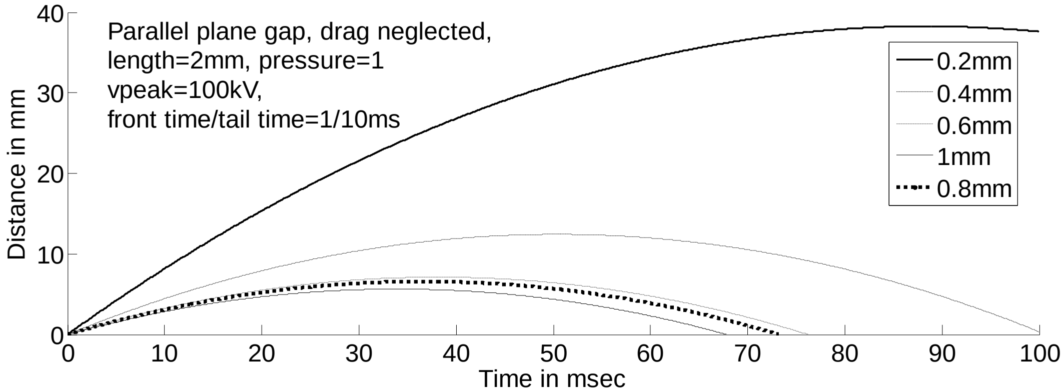

Fig. 9: Effect of radius of filamentary wire particle on its motion through parallel plane gap.

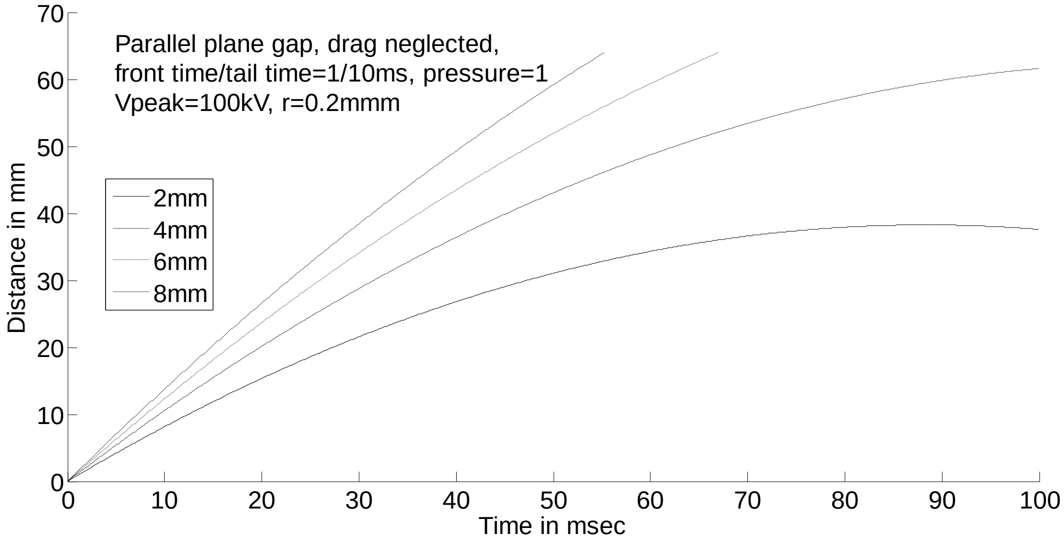

Fig. 10: Effect of length of filamentary wire particle contamination through parallel plane gap under applied impulse voltage.

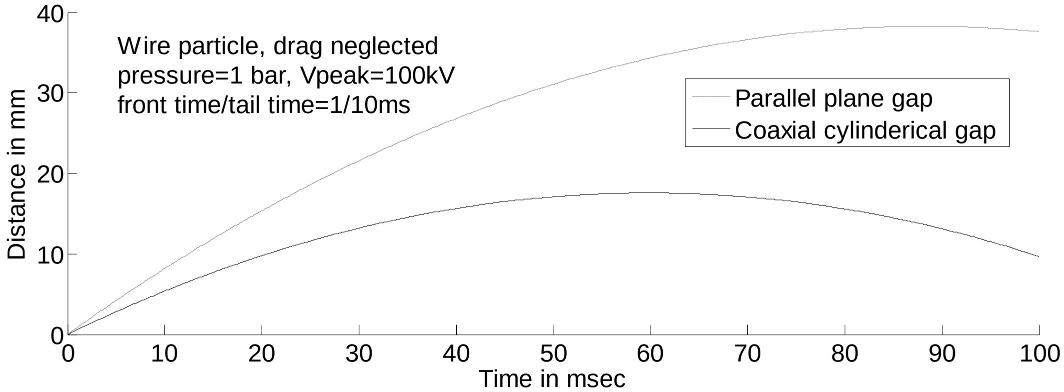

Fig. 11: Effect of gap configuration on the motion of the contaminating wire particle.

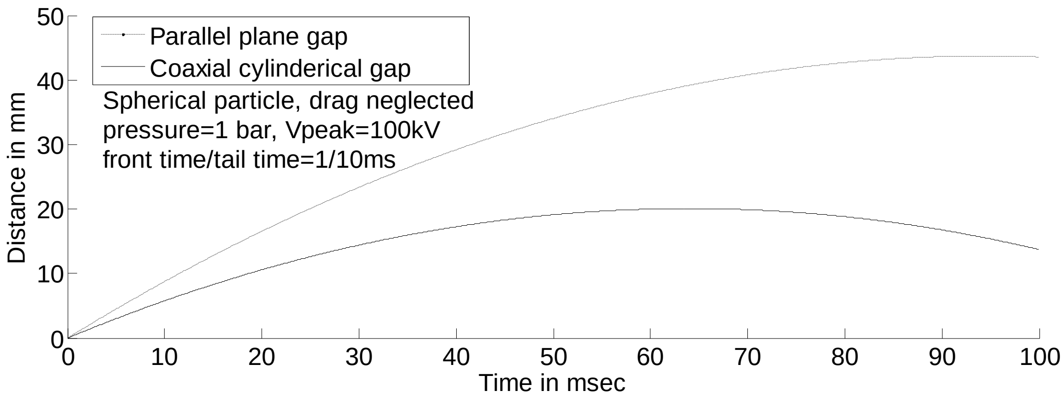

Fig. 12: Effect of gap configuration on the motion of the contaminating spherical particle.

V. Conclusion

In this paper, a model has been formulated to simulate the movement of particle in insulating gas in gas insulated system (GIS). The exact formulae for the particle displacement, lifting voltage, and lifting electric field for different contaminating particle configurations (spherical and wire) standing on a ground plane in a different gap in pure SF_6 insulating gas were used to study the dynamic behavior of these particles which affect on the dielectric strength of that gas. The equations of particles motion have been formulated and numerically solved when a contaminating metallic particle moves in different gap configurations such as parallel plane and coaxial cylinders gap. Several dynamical phenomena have been investigated to illustrate the parameters that affect on the particle motion.

The applied voltage plays an important role on the movement of the contaminating particle. An increase of the applied voltage, the particle will be faster.The drag force impedes the movement of the contaminating particle, therefore, in case of darg fully accounted for the motion of the particle is slower than that in case of drag neglected. In case of the spherical particle, when the particle radius increases, it means that the volume of the particle and its weight increases, the movement of the particle will be reduced. In case of longitudinal (wire) particle, an increase of the particle length results in faster motion of the contaminating particle. The particle will be more faster in the case of parallel plane gap than its motion in coaxial cylinders gap.

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