Simulation and Motion Analysis of Spherical Free Conducting Particle between Coaxial Electrodes

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***Abstract*- The trend of development of Gas Insulated System (GIS) recently includes: miniaturization, intelligentization and high reliability. This needs a higher insulation performance of GIS. Free conducting particle in GIS is a main reason that causes the degradation of GIS insulation. Free conducting particle will bring a high risk to GIS insulation when it approaches to the high voltage conductor or reaches the disc-type insulator surface. Particle in radial non-uniform electrical field is apt to move along the radial direction in GIS, and probably moves into the high insulation risk region. According to the distribution of the electrical field between coaxial electrode systems, the dynamic model of spherical particle in axial non-uniform electrical field under AC voltage is amended. The motion phenomenon of particle is explained by solving the dynamic equations. Gravitational force, Coulomb force, electrical gradient force and gas viscous force are considered. Improving the applied voltage can increase the motion distance in vertical direction. The criterion can explain the incremental quantity of the motion onset voltage of particle in uniform field under AC voltage than it under DC voltage. Observations indicate that voltage exerts an incremental effect on maximum height. By analyzing improved dynamic model of spherical particle, another novel criterion to judge the penetration of the motion of spherical particle in uniform field under AC voltage is brought forward, as well.**

I. INTRODUCTION

At present, the use of GIS in many cases the use of imported production equipment in China. Due to its high cost, an increase of China's UHV transmission network construction costs. At present, the main development direction of GIS is miniaturization, compactness, intelligence and high reliability. In order to further reduce the GIS volume and improve the working voltage of GIS, improving the insulation reliability of GIS becomes an important research topic in high voltage research field [1][2].

The uniformity of electric field, SF_6 insulation performance is brilliant enough. With the increase of the electric field inhomogeneity, SF_6 advantage of insulation will no longer exist. Therefore, GIS insulation design is much emphasized on the uniformity of electric field distribution. Due to this characteristics of SF_6, partial discharge in the gap is easy to form a breakdown discharge. The partial discharge starting voltage is close to the gap breakdown voltage. Therefore, it is necessary to avoid partial discharge in GIS design [3].

The corona in GIS mainly comes from the surface protrusions and the free conducting particles. The initial corona voltage of the electrode is mainly affected by the surface morphology of the electrode, and the influence of the gap distance is second. In order to reduce corona caused by electrode surface roughness, the minimum surface roughness of the electrode in the GIS is: inner electrode $R_a \leqslant 6.3\mu m$, outer electrode $R_a \leqslant 50\mu m$, this requirement could achieve by sanding, etc. Therefore, the free conducting particles become a major cause of local non-uniform electric field in the GIS insulator.

In the application of a certain voltage conditions, the free conducting particles will move in the GIS cavity by the Coulomb force in the electric field, may therefore lead to GIS insulation breakdown failure. For a coaxial cylindrical electrode system, which is often found in GIS, the free conducting particles originally at the bottom of the grounded enclosure are subject to Coulomb forces after a certain charge quantity is applied and float from the inner surface of the grounded enclosure [4].

As the frequency AC voltage a cycle of time is only 20 ms, so the particles in the gas gap can stay in the time to several cycles. And the direction of the Coulomb force reverses several times due to the change of the Coulomb force during the flying process. Therefore, the movement of particles in the course of collision with the electrode will change several times, resulting in the movement of particles under AC voltage Behavior complexity [5].

In this paper, we start form force analysis of spherical free conducting particle in the coaxial electrode systems, then descript the lift-off condition of spherical particles, after that, we make a program to calculate the trajectory of particles under AC voltage. At last, an equation to calculate the lift-off limited jump height is expressed.

II. FORCE ANALYSIS OF SPHERICAL FREE CONDUCTING PARTICLE

The length of GIL unit, mainly on long, straight tube, can be as long as 10 meters to 18 meters. The axial non-uniform

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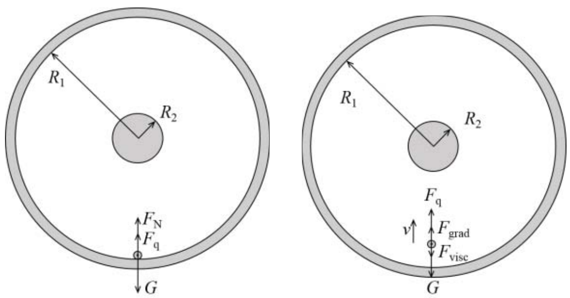
electric field can be neglected in most of the area within the cavity which far away from the basin insulator and pipe interface, thus, the radial electric field could be considered when we deal with force analysis of spherical free conducting particle. Before particle lift off, the gravitational force G, Coulomb force F_q and normal force F_N mainly acts at the particle; after particle lift off, the gravitational force G, Coulomb force F_Q, normal force F_N, electrical gradient force F_{grad} and gas viscous force F_{visc} mainly acts at the particle. The force conditions are shown in Fig. 1 (a) and (b). In the following discussion, the voltage of high voltage conductor is taken as a positive voltage, and the vertical direction is taken as a positive direction.



(a) Before particle lift off (b) After particle lift off

Fig. 1. Force conditions of spherical free conducting particle

The gravitational force G always acts on the spherical particle can be expressed as

$$G = -\frac{4}{3}\pi a^3 \rho g \tag{1}$$

Where a denotes the particle radius, g the gravitational acceleration, ρ the particle density.

The Coulomb force F_q magnitude depends on the electric field of particle position, this force can be expressed as

$$F_q = -kqE \tag{2}$$

Where k denotes the correction factor caused by the electron-image force, q the charge carried by the particle, and E the intensity of the electric field at the particle.

When the particles with a certain charge in the vicinity of the electrode surface, the electrode surface will cause a mirror charge. The mirror charge creates an electron-image force on the particles, changing the Coulomb force of the particles, k the correction factor of the Coulomb force due to the electron-image force. When the distance between the particle and the electrode is less than 5 times the particle radius, $k = 0.832$, when the particle is far away from the electrode surface, $k = 1$[6].

For a coaxial electrode system, the electric field strength somewhere between the electrodes can be expressed as

$$E = \frac{U}{(R_1 - x)\ln\frac{R_1}{R_2}} \tag{3}$$

Where U denotes the instantaneous voltage of the bus, x the distance from the shell to the particle, R_1 the radius of the shell, R_2 the radius of the high voltage conductor. For the spherical conducting particle radius is much smaller than the coaxial cylindrical electrode gap ($a << R_1$-R_2), before the particles lift-off, it always stand still with the bottom of the case, the shell can be used to estimate the location of the electric field strength of the location of the electric field strength, as $x = 0$ case.

When spherical particles lift-off or collision with the shell, the amount of charge can be related to the instantaneous value of the electric field strength. The charge quantity can be expressed as

$$q = \frac{2}{3}\pi^3 a^2 \varepsilon_0 \varepsilon_r E \tag{4}$$

Where ε_0 is the permittivity in vacuum and ε_r is the relative permittivity of the gas. It can be seen from the formula, the particle charge with the power frequency phase of the collision, when the particle collision time is located in the peak power frequency voltage, the particles with the largest amount of charge. Regardless of micro-discharge during the particles are flying in the gap, the charge quantity of the particles charged could be calculated with the previous collision with the electrode.

The electric field of coaxial electrode system where the free conducting particles is not uniform electric field, electrical gradient force also acts at the particle. In the non-uniform electric field, the polar force of the dipole formed by polarization is different in the direction of the electrostatic force, so the electric force will form the electrical gradient force [7]. The electric field gradient force applied to the spherical conducting particles can be calculated using Equation (5).

$$F_{grad} = 2\pi a^3 \varepsilon_0 \varepsilon_r |\nabla E^2| = 4\pi\varepsilon_0\varepsilon_r \frac{a^3}{r^3}\left(\frac{U}{\ln\frac{R_2}{R_1}}\right)^2 \tag{5}$$

When the particles begin to move after lift-off away from the gap, the gas viscous force F_{visc} will act at the particles. the direction of F_{visc} is opposite to the movement of the particles. In the field of fluid mechanics, the Reynolds number is used to characterize the fluid flow. Before the calculating the viscosity of the gas, we need calculate the Reynolds number to determine the viscous drag type. Reynolds number can be calculated using (6)

$$Re = \frac{2a\rho_g v}{\mu} \tag{6}$$

Where v denotes the particle velocity, ρ_g the density of SF_6 gas, and μ the viscosity coefficient of SF_6 gas.

For the free conducting particles in GIS, the typical velocity satisfies v> 0.2 m/s, and the typical diameter of free particles in GIS can satisfy a> 50μm, thus, the range of Reynolds number is at least Re> 5. According to the theory of fluid mechanics, for large Reynolds number ball around the flow resistance [8], usually using the empirical equation (7)

$$F_{visc} = \left(\frac{24}{Re} + \frac{6}{1+\sqrt{Re}} + 0.4\right)\pi a^2 \frac{\rho_g v^2}{2} \tag{7}$$

III. CALCULATION OF SPHERICAL FREE CONDUCTING PARTICLE MOTION STATE

For the spherical free conducting particles, we analysis the force condition before the particles lift-off, with the applied voltage increases, the Coulomb force which acts at the particles is greater than gravity, then the particles satisfies the lift-off conditions

$$F_q \geq G \tag{8}$$

Put equation (1), (2) and (3) into equation (8), we can get the spherical particle lift-off conditions in the coaxial electrode system

$$\mathrm{U} > \frac{1.096}{\pi} R_1 \ln\frac{R_2}{R_1}\sqrt{\frac{\rho a g}{\varepsilon_0 \varepsilon_r}} \tag{9}$$

Where U is the RMS voltage of high voltage conductor.

The behavior of the particles moving between the electrodes after lift-off is determined by the equation (10)

$$\mathrm{m}\frac{d^2x}{dt^2} = F_{\mathrm{q}} + G + F_{\mathrm{grad}} + F_{\mathrm{visc}} \tag{10}$$

When the particles at a certain speed impact with the shell, the particles will rebound. When the two objects impacts, the separation speed is proportional to the collision speed. The speed before and after the collision which taking consider of the non-elastic collision process of particles and the GIS shell can be expressed as:

$$v = -C_{\mathrm{R}} v_{\mathrm{f}} \tag{11}$$

Where v, v_{f}, denotes the speed before and after the collision, C_{R} the collision recovery factor.

In the known particle initial conditions, the particle motion equation can be solved to get the movement of particles. In this paper, we use the multi-step linear algorithm to compute the particle motion state, get the motion trajectory of particle by using a calculation program. The program flow chart is shown in Fig. 2.

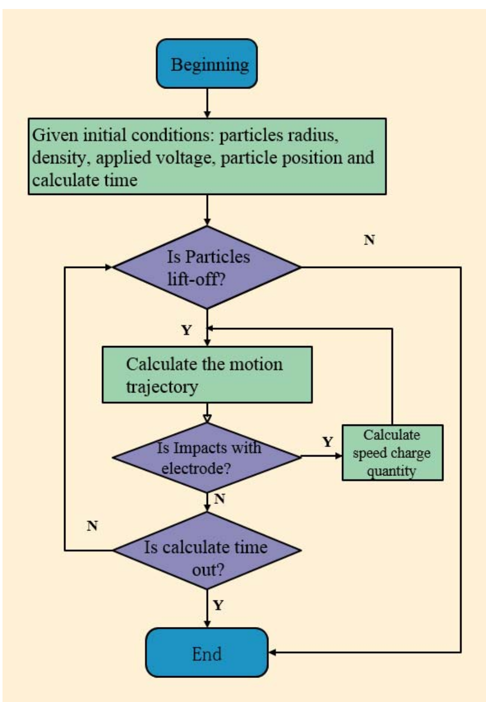


Fig. 2. The flow chart of free conducting particles simulate program

The initial parameters of particle movement calculation program are as follows: particulate material density of = 2700kg/m^3 (aluminum), vacuum dielectric constant ε_0=8.8542×10^{-12}F/m, SF_6 gas relative permittivity ε_{r} = 1, gravity acceleration g = 9.8 m/s^2, viscosity coefficient of SF_6 gas η = 1.54×10^{-5}Pa·s, diameter of the high voltage conductor is 18mm, the radius of GIS shell is 88mm, collision recovery factor C_{R} = 0.75. Using the equation (10) to calculate the experimental coaxial electrode system, the spherical particles of the lift-off voltage of 29.8kV, applied U = 50kV at high voltage conductor, for a radius of 1mm spherical particle trajectory shown in Fig. 3.

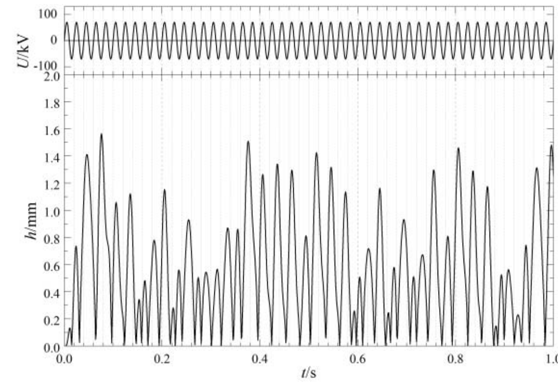


Fig. 3. The motion trajectory of a radius of 1mm spherical particle

It can be seen from Fig. 3 that the trajectories of the free conducting particles under the power frequency voltage have obvious differences from the DC voltage. The particle trajectories under the power frequency voltage have greater stochastic, because the different time of collision between the particles and the electrode lead to the different charge quantity of the particles, thus affecting the force of the particles, and the force of the particles changes with time and space. In addition, the free-conducting particles under DC voltage must collide with the high-voltage conductor electrode after lift-off, but the pulse height under the power frequency voltage is controlled by the power frequency voltage, and has a limited height at a given voltage because of varies of the voltage phase, the positive and negative Coulomb force acts the particles alternately, so that it cannot always accelerate the movement, which there is lift-off limited height.

Due to different sizes and material of particles, the sensitivity of the external voltage are different between the different particles, so the definition of the normalized voltage to the applied voltage and the lift-off voltage ratio K_{U}, as shown in equation (12) below.

$$K_{\mathrm{U}} = \frac{U}{U_{\mathrm{Lift-off}}} \tag{12}$$

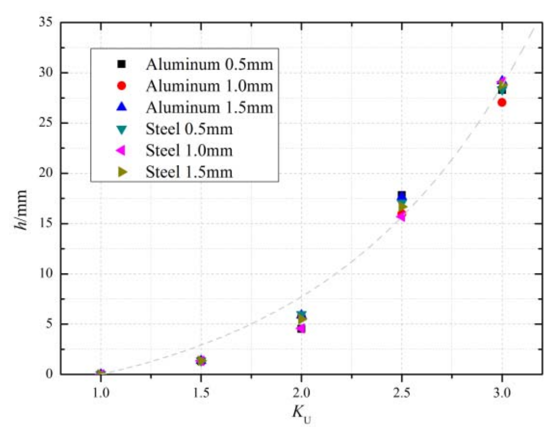


Fig. 4. The relationship between the lift-off limited height and the normalized voltage (different particle type)

In the simulation conditions described above, the relationship between the lift-off limited height and the normalized voltage as shown in Fig. 4. It can be seen that the relationship between the lift-off limited height h and the normalized voltage K_U is independent of the particle size and material, and increases monotonically with the normalized voltage under a given electric field.

Using the formula (13) as shown to fit the relationship between the lift-off limited height and normalized voltage, the results shown in Table 1.

$$h = A(e^{K_U - 1} - 1) \tag{13}$$

TABLE I
FITTING RESULT OF THE RELATIONSHIP BETWEEN THE LIFT-OFF LIMITED HEIGHT AND NORMALIZED VOLTAGE
(DIFFERENT PARTICLE TYPE)

Particle type	Steel particle			Aluminum particle		
	0.5mm	1.0mm	1.5mm	0.5mm	1.0mm	1.5mm
A	4.467	4.426	4.480	4.465	4.247	4.597

It can be seen from Table I that particle material and size have little effect on the lift-off limited height of the free conducting particles. Using equation (13) leads a preferably fit result to estimate the lift-off limited height of particles with different materials and sizes.

Holding the coaxial electrode system structure unchanged but scaled it up.18mm/88mm, 90/440mm and 180/880mm were used as initial conditions to study the applicability of (13) to coaxial electrode systems of different sizes with the same structure, using the aluminum spherical particles with diameter of 1mm. The simulation results are shown in Fig. 5.

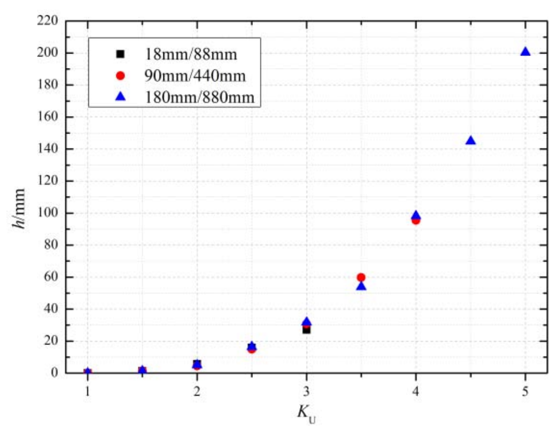


Fig. 5. The relationship between the lift-off limited height and the normalized voltage (different coaxial electrode system type)

As can be seen from Fig. 5, the coaxial electrode system is scaled in equal proportion, but the relationship between the lift-off limited height and normalized voltage still presents the same law, i.e. the height increases exponentially with the normalized voltage. Using the formula (14) to fit the height in different coaxial electrode system, the results shown in Table II. As can be seen from Table II, even though the coaxial electrode system is scaled up, but the height of the conducting particles is still very similar. Thus, using the formula (14), the limited height of particles with different GIS sizes can be fitted.

TABLE II
FITTING RESULT OF THE RELATIONSHIP BETWEEN THE LIFT-OFF LIMITED HEIGHT AND NORMALIZED VOLTAGE
(DIFFERENT COAXIAL ELECTRODE SYSTEM)

Coaxial electrode system type	18mm/88mm	90mm/440mm	180mm/880mm
A	4.247	5.036	4.076

From the results of Table I and Table II, it can be concluded that the equation (14) can be used to calculate the lift-off limited height of the free conducting particles of different materials and different sizes in the coaxial electrode system, the value of A is between 4 and 5.

IV. CONCLUSION

Based on force analysis of spherical free conducting particle and the calculation of particles motion state, the results are summarized as follows:

1. Before particle lift off, the gravitational force G, Coulomb force F_q and normal force F_N mainly acts at the particle; after particle lift off, the gravitational force G, Coulomb force F_Q, normal force F_N, electrical gradient force F_{grad} and gas viscous force F_{visc} mainly acts at the particle.

2. The free-conducting particles under DC voltage must collide with the high-voltage conductor electrode after lift-off, but the pulse height under the power frequency voltage is controlled by the power frequency voltage, and has a limited height at a given voltage.

3. The height increases exponentially with the normalized voltage with different GIS size or particles size and material.

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