Motion of Conducting Particles Causing Inadvertent Outages in GIS

M. S. Indira and T. S. Ramu
Dept. of High Voltage Engineering
Indian Institute of Science
Bangalore, India

ABSTRACT

Inadvertent failure of a HV gas-insulated system (GIS) is traced to a seemingly innocuous mechanism in particle-induced breakdown. Impending dangers from inconspicuous conducting particles in a large physical system are quite intriguing. The dynamic behavior of the particle due to electric field/particle/fluid medium interaction is a complex phenomenon. To understand this interaction, a credible database has been generated for the field-induced motion of the particles on a physical prototype model. Induced surface charge acquired by the particle is calculated based on the proposed model (field calculations) and by considering it to be a prolate ellipsoid. Methods for deactivating potentially dynamic particles using dielectric coated active parts and grounded enclosures, and a novel technique called reverse polarity charging have been suggested. Performance of GIS in the presence of metallic particles has been studied with bare electrodes and with dielectric coatings of different conductivities with a view to obtain an optimal value of the conductivity.

1 INTRODUCTION

GAS insulated substations or totally enclosed substations have been a major innovation in power transmission and distribution with proven reliability, and maintenance-free operation. As one is already aware of the attractive features of a gas-insulated system (GIS), they also suffer from certain drawbacks. One of them is outage due to seemingly innocuous conducting particles, which accounts for nearly 50% of the GIS failures. Probability of breakdown due to particles is in a region of maximum local field, which may be defined as the statistical residence time. The field at the particle tip exceeds the limiting dielectric strength of the gas, at least locally, initiating a corona discharge, which in time develops into a breakdown. The voltage withstand capability of GIS under normal service conditions due to high concentration of particles depends on numerous interrelated factors such as the length, size, and nature of the particles, position of particles with respect to the HV points, dynamics of particles under the electrostatic force and gravitational field, gas pressure, and condition of the insulator surface. Recent studies have indicated that the GIS can be operated successfully in the presence of particles. Some of these measures are either expensive or pose irreconcilable difficulties in their operation.

In order to be able to understand the behavior of particles in an electric field, dynamic aspects are to be studied. In the simplified model proposed in an earlier work by the authors [1], the lift-off stresses are determined and hence the induced surface charges. The induced charge is also determined by considering the particle to be a prolate ellipsoid. Hence the lift-off force is estimated which is also an essential parameter in determining the particle dynamics. In order to reduce the adverse effect of the metallic particles, the earlier literature [2] reports that coated enclosures may be used as a possible method to restrict the motion of the particles. In the present context a novel technique is suggested, which is simple, cost effective and reliable in passivating the particles and thus preventing inadvertent outages.

2 THEORETICAL

Certain theoretical aspects of the motion of a particle in an electric field, and its dynamic behavior under the action of various forces aiding and inhibiting the motion of the particle, are considered. Motion of metallic particles in GIS are extensively studied by several authors [3], because particle movement plays a crucial role in the breakdown of the gaseous medium. These calculations assume, among other simplifications, that the net surface charge of the particle remains constant.

2.1 ESTIMATION OF INDUCED CHARGE ON THE PARTICLE

A rigorous analysis of the induced surface charge density σ on a particle and its interaction with the electric field in which it is situated, is very complex and often closed-form solutions are not possible. However, an approximate treatment for calculating σ to a fair degree of accuracy is attempted. At the outset, a prolate ellipsoidal particle is considered in a nearly homogeneous 3-D field with a possible axial symmetry as shown in Figure 1. The potential at any point between the two electrodes is a function of coordinate axis and the dimension

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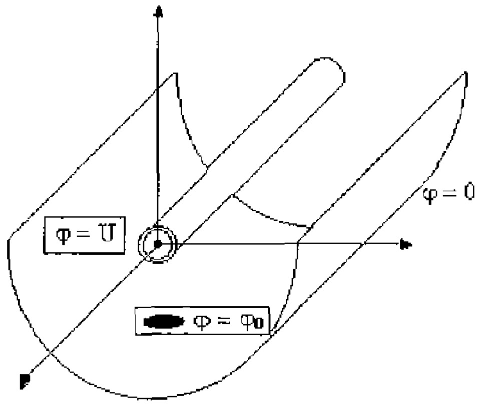

Figure 1. Schematic representation of electrode geometry and ellipsoidal particle in a 3-D coordinate system.

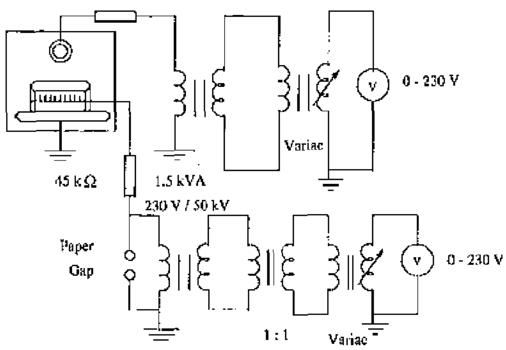

Figure 2. Circuit arrangement for reverse polarity charging.

of the ellipsoid. The induced charge on the surface of the conducting ellipsoid can be obtained as in

$$Q = -8\pi\varepsilon_o A \tag{1}$$

where $\varepsilon_o = 8.854\times10^{-12}$ F/m is the permittivity of free space, and in which A is the elliptic integral in 3-D taken over zero and infinity on the variable θ as

$$A = -\varphi_0 \int_0^\infty \frac{d\theta}{\sqrt{(a^2+\theta)(b^2+\theta)(c^2+\theta)}} \tag{2}$$

where a, b, and c are the semi-axes of the ellipsoid. In this calculation, the constant A is derived based on the assumption that the potential at the position of particle is the same as in the absence of the particle. The value of this integral can be obtained either by numerical integration or referring to a table of elliptic integrals. The surface charge density σ is given by

$$\sigma = \frac{Q}{4\pi abc}\frac{1}{\sqrt{\frac{X^2}{a^4}+\frac{Y^2}{b^4}+\frac{Z^2}{c^4}}} \tag{3}$$

The induced surface charge on the semi-ellipsoidal particle quadrature to the field, according to Felici, is given by

$$Q = 2\pi\varepsilon_o rlE \tag{4}$$

where l is the length of the particle, r the radius of the particle, and E the field seen by the particle.

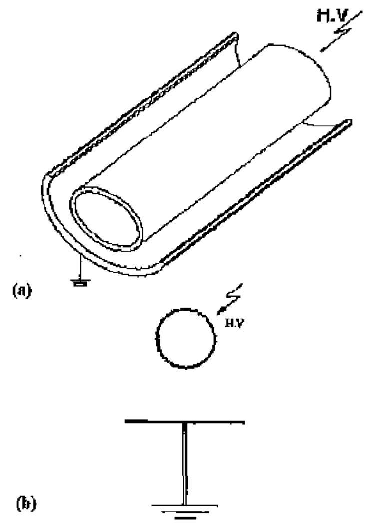

Figure 3. Electrode configuration. (a) Electrode type 1. (b) Electrode type 2.

2.2 THE DYNAMIC ASPECTS OF THE PARTICLE

The motion of a particle under a time changing ac electric field is more complex than under direct fields, since the space charge on the particle interacts with changing fields. In a coaxial system, the particles do not cross the gap unless the electric field is very high and is affected over a number of voltage cycles, after a series of bounces [3]. The maximum altitude attained by the particle is determined by the applied voltage and the loss of charge, due to charge transfers, if any, to the medium either by corona or as a pulseless discharge.

2.3 THE LIFT-OFF FIELD

This may be defined as the critical field at which the particles change their position from rest. It is a function of the initial distribution and orientation of the particles with respect to the electrodes, which determines the subsequent particle dynamics. The initial motion at t_0 is field dependent, and is observed to be independent of the type of gas medium, its pressure, and the length of the particles. Felici suggests approximations for an ellipsoidal particle with its initial position quadrature to the field as

$$E_L = \sqrt{\frac{\rho g r}{1.43\varepsilon_0}} \tag{5}$$

According to Asano *et al.* [5], and based on half-cylinder and full-cylinder geometry, the lift-off stress in kV/m is given as

$$E_L = 808\sqrt{a\rho} \tag{6}$$

and

$$E_L = 880\sqrt{a\rho} \tag{7}$$

where a is the radius of the particle, and ρ the density of material.

3 EXPERIMENTAL

The stainless steel prototype used to study the particle dynamics for estimating and assessing the lift-off voltages nearly simulated the actual conditions in a GIS. The chamber was equipped with a Wilson seal

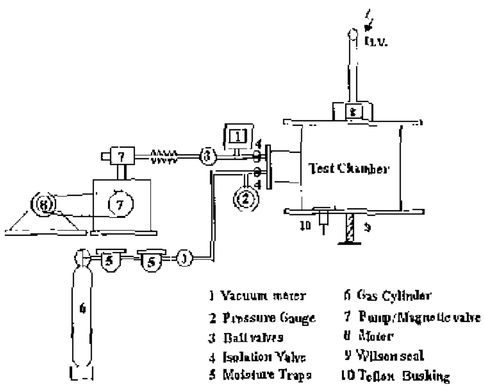

Figure 4. Gas handling system.

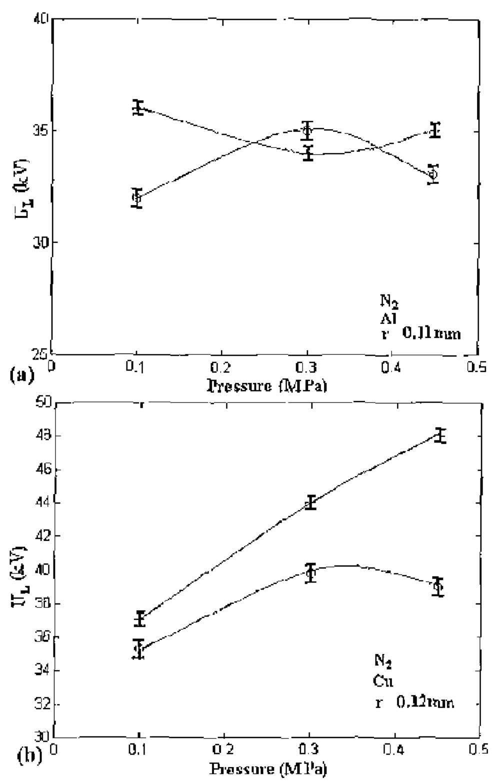

Figure 5. Measured lift-off voltage as a function of pressure o bare electrode type 1, + bare electrode type 2.

to facilitate the positioning of the particles. Circular ports provided with toughened glass windows allowed visual observation, illumination and connection for the gas handling system. The controlled pressurized chamber incorporated several additional features such as HV stress grading of the leadthrough. Spraying of charges of either polarity was achieved by reverse-polarity energizing with an endeavor of passivating the particles. This technique consisted in applying a voltage proportional to the main HV supply, but opposing it by 180° using a separate auxiliary transformer as shown in Figure 2. Isolation between the two HV sources was obtained by taking the charging power supply

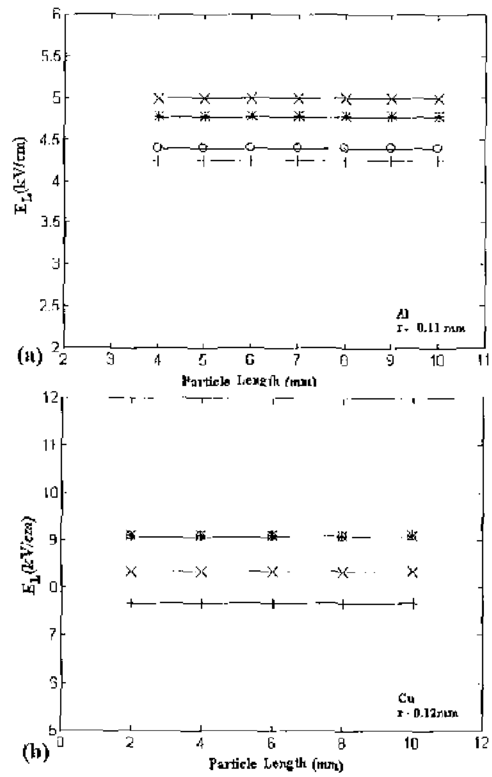

Figure 6. Estimated lift-off stress as a function of particle length. + proposed model, * Felici's model, o Asano-HCM, × Asano-FCM

through a Teflon bushing located at the bottom of the chamber.

3.1 ELECTRODE CONFIGURATION

Two different electrode geometries, a split-cylinder, thick walled hollow tubular structure and a Rogowski-profiled circular plate thick walled hollow tubular structure, have been considered in the series of experiments reported here. For the sake of easy identification they are designated as Type 1 and type 2 electrode systems respectively, as shown in Figure 3. Furthermore these configurations have been used both as bare and as coated systems. The electrode surfaces were highly polished, degreased, and dried before the start of the experiments. A set of geometrically formed and polished electrodes were given a dielectric coating using appropriate dielectric materials such as polyethylene, polypropylene and certain antistatic materials which are obtained by doping certain epoxy resins with conducting materials of selected grain sizes such as pure graphite. The coating thickness varies for different material mentioned here and is in the range of 3 to 20 μm.

3.2 GAS HANDLING SYSTEM

Figure 4 shows details of the gas handling system. The prototype of the GIS chamber was equipped with pressure vacuum valves and gauges to monitor the degree of prior evacuation and final pressure. The chamber was evacuated to a pressure of 1 mPa before filling with the gas medium. Pressures were maintained between 0.1 to 0.5 MPa. The gas was passed through moisture traps ($CaCl_2$ and silica gel) with

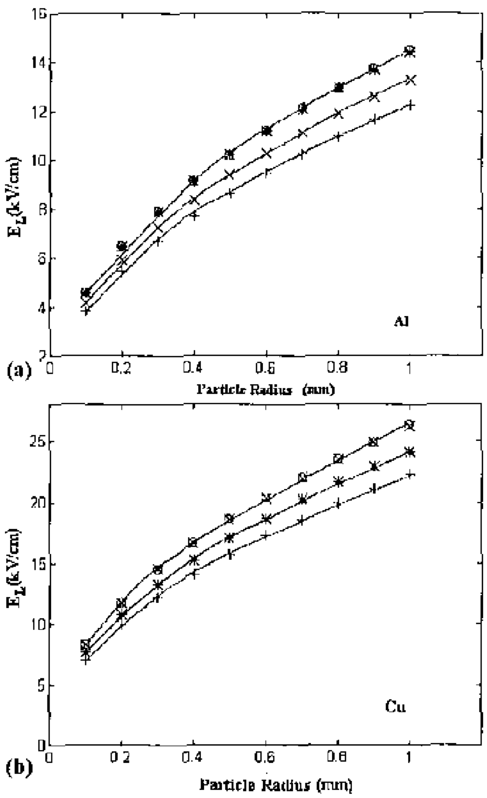

Figure 7. Estimated lift-off stress as a function of particle size. (a) Al particle, (b) Cu particle. o Felici's model, + proposed model, * Asano-HCM, × Asano-FCM.

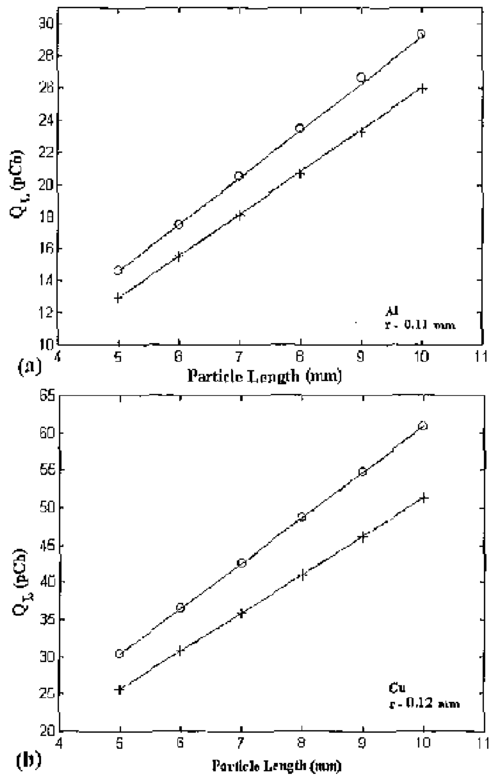

Figure 8. Calculated induced surface charge Q_l, at lift-off o Felici's model, + proposed model.

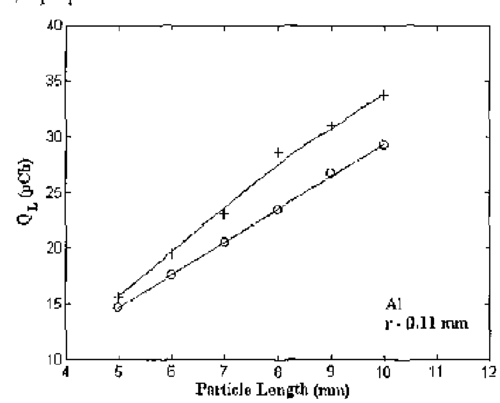

Figure 9. Calculated induced surface charge Q_l, at lift-off. o Felici's model, + proposed model.

a regulated flow rate. The evacuation and the gas inlet systems were isolated using high quality ball valves. Safety valves were incorporated to let out excess gas when necessary.

3.3 TEST AND MEASURING EQUIPMENT

High ac voltage at power frequency was generated by an HV cascaded measuring (test) transformer rated for 10 kVA, 220 V/110 kV (GE). The system was observed to be partial discharge (PD) free up to 1.2× the rated voltage. The low voltage supply to the transformer came from a regulator rated for 60 A, 240 V, and 50 Hz. A current limiting resistor, also PD free, with a resistance of 40 MΩ provided the required current protection. An auxiliary voltage transformer rated for 1.5 kVA, 230 V/50 kV along with a 25 kVA, 110 A, 230 V variac and a 45 kΩ current limiting resistor were used in the experiments to study the passivating effects of reverse polarity charging. The necessary phase shift in the voltage waveform was derived from an intermediate 1:1 isolation transformer. Voltage across the specimen was obtained by subtracting vectorially the voltage drop across the current limiting resistor from the source voltage.

Measurement of resistivity helps in predicting the ability of the insulating material to dissipate the buildup of electrostatic charge. Materials that are coated or chemically treated to contain an internal antistatic agent have static dissipative characteristics that are a function of surface resistivity. A surface/voltage resistivity probe Model 803A measured the resistivity of the coating materials. The design of the model probe electrode configuration was derived from the applicable formulae mentioned in ANSI/ASTM D257 [6].

In the series of experiments reported here, filamentary particles of aluminum and copper were chosen, since they are more common in GIS and are very critical to the system performance. No attempt was made to smoothen the wire ends in order to simulate the actual condition in a GIS.

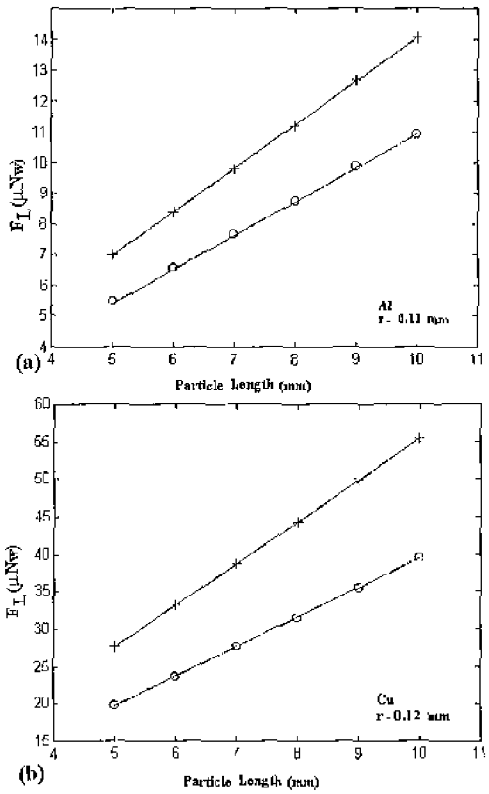

Figure 10. Estimated electrostatic force at lift-off as a function of particle length. o Felici's model, + proposed model.

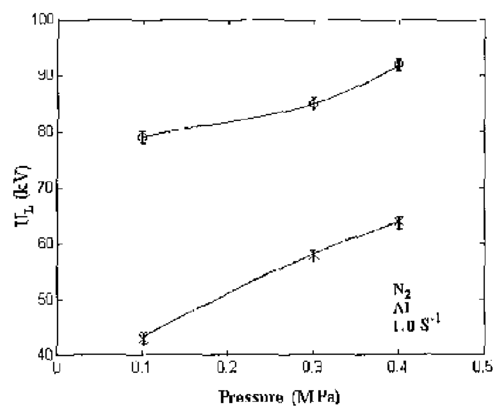

Figure 11. Measured lift-off voltage as a function of pressure. + dielectric coated grounded enclosure, o both electrodes dielectric coated.

4 RESULTS AND DISCUSSIONS

Particles in practical systems have a wide variety of sizes, shapes and are materials of differing conductivities and densities. Many of these factors influence the particle charging and charge leakage mechanisms, as do the dielectric properties of the gas and its pressure. Concomitantly, these factors also have a significant influence on the motion of the particles and the degree to which they migrate into the high field zone.

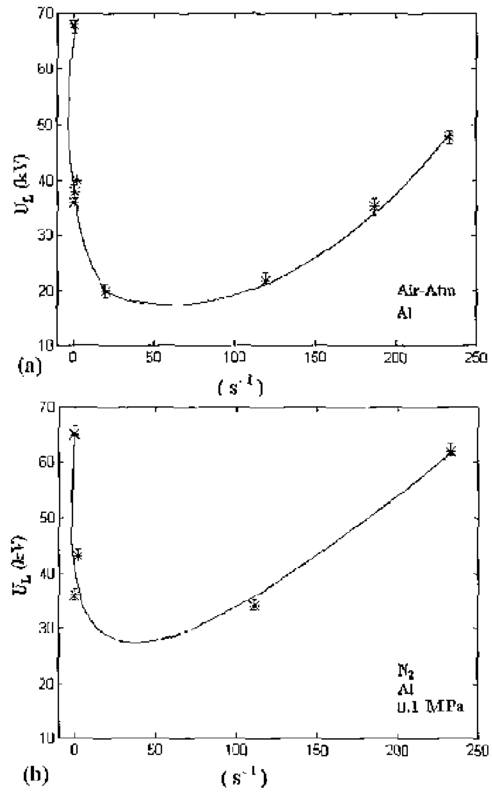

Figure 12. Measured lift-off voltage as a function of conductivity of the coating material. (a) Air, (b) N_2.

4.1 RESULTS

The lift-off voltages as a function of pressure for aluminum and copper particles for the two electrode systems are depicted in Figures 5(a) and (b). The lift-off voltage seems to be independent of the electrode system. The lift-off stresses obtained from the proposed model [1] are compared with Felici [4] and Asano *et al.* [5], and for both aluminum and copper particles are shown in Figures 6(a) half cylinder model (HCM) and (b) full cylinder model (FCM). Figures 7(a) and (b) depict the variation of the lift-off voltage with the size of the particle. The obvious observation is that the lift-off voltage does not depend on the particle length and pressure of the medium but depends on the particle material density and the size.

It may be observed that the plotting positions have been indicated with the mean value centered around one standard deviation on the mean value, assuming that the data at any one voltage have a Gaussian scatter. This procedure of plotting is used in Figures 5 and 11 to 14. Actually, on the graphs such scatter does not appear to be very significant.

The induced surface charge acquired by the particle as a function of length at lift-off based on the proposed model and Felici's formula has been compared. Figures 8(a) and (b) amply support agreement between the two modes of field calculation. The induced surface charge calculated by considering the particle to be prolate ellipsoid, compares well with the model based on Felici's calculation as shown in Figure 9. The electrostatic force experienced at lift-off as a function of length for

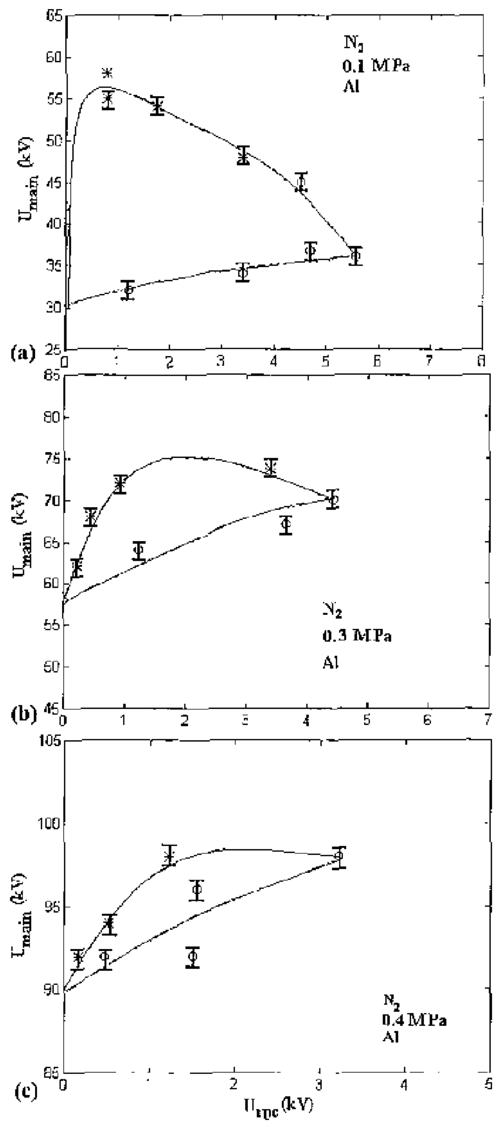

Figure 13. Hysteresis effect with bare electrodes. (a) 0.1 MPa, (b) 0.3 MPa, (c) 0.4 MPa.

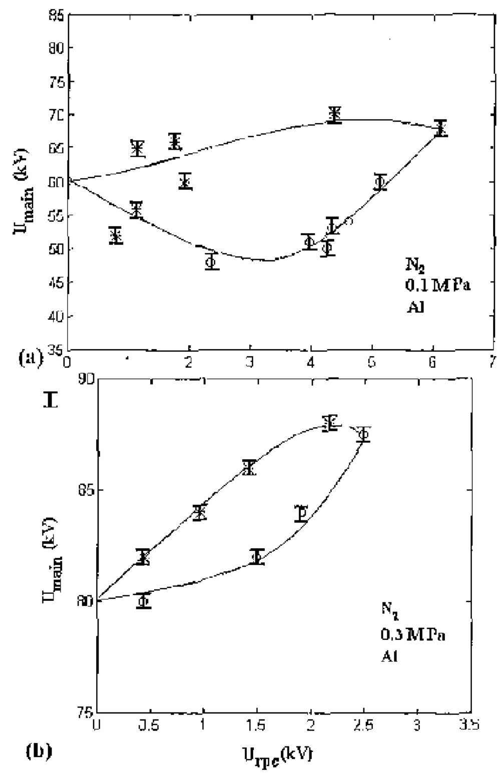

Figure 14. Hysteresis effect with coated electrodes. (a) 0.1 MPa, (b) 0.3 MPa.

a given size of the particle is estimated and given in Figures 10(a) and (b).

The dielectric coating of a metallic surface affects the particle charging mechanism. Coating the enclosure increases the lift-off voltage considerably. Various dielectric materials have been tried by the authors [1]. Figure 11 suggests that there is considerable improvement in the performance, by having both electrodes coated rather than with only coated enclosure or with bare electrodes. A critical minimum has been observed with considerable repeatability in both air and nitrogen, as depicted in Figures 12(a) and (b), a plot of the variations of U_L with conductivity of the coating materials. Similar behavior has been observed in nitrogen at pressures of 0.3 and 0.4 MPa.

In an effort to mitigate the problem of particle charging and the ensuing breakdown, a new method of stripping the charge was tried out on both bare and coated electrodes at different pressures of the gas. A plot of the applied voltage U_m as a function of reverse polarity charging voltage U_r at different pressures are shown in Figures 13(a), (b) and (c) exhibited a nearly hysteresis (closed two-loop curves) behavior. The area enclosed could be related to the charge and hence the energy accumulated by the particle.

4.2 DISCUSSION

The calculation of the actual field seen by the particle is quite complex. In this work, an approximation has been made in which the particles are treated as ellipsoids and in the limit the coordinates are made small enough so as to make them thin strip of wires. The fields seen by the particle in such an event is estimated to be 2 to 5× the actual field at that point.

The empirical relations suggested by Felici [4] and Asano *et al.* [5] can be used to evaluate the surface charge accumulated by the particle. The small differences in the charges calculated using the above mentioned relations and the proposed model is believed to be due to the approximation to the field suggested above.

In the literature [7, 8] one of the methods suggested for mitigating particle activity is to use dielectric coated electrode. By using suitable coatings, mentioned earlier, the micro-projections are smoothened, reducing the bounce heights and thus restricting the particle movement. It may be seen that the concept of electrical stress grading in cables

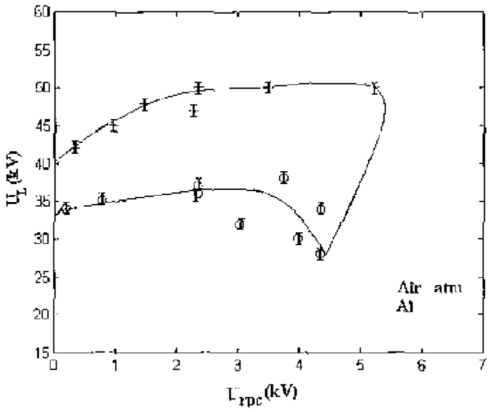

Figure 15. Hysteresis effect with bare electrodes (air).

and generator stator bars could be involved in GIS by the use of semiconducting coating. If the coating is treated as a lumped equivalent RC circuit, with a time constant larger than corresponds to the power frequency, then the charge acquired by the particle will be smaller than the required charge for lift-off and hence results in an increase in the lift-off voltage levels. It is also seen that coating both the HV electrode and the grounded enclosure enhances the performance of the system.

It has been reported in [9] that the mechanism of charging of particles is due to PD micro-discharges at low pressure and high fields. With alternating voltages, charges were found to accumulate in the negative half cycle and discharge in positive half cycle. The charge quantity Q_n of the PD in the negative cycle was found to be larger than Q_p in the positive half cycle, at low pressures, in particular. The difference $(Q_n - Q_p)$ of the charges generated every cycle resides on the particle until the total charge reaches the threshold value for lifting.

In the light of the above discussion, the authors proposed a new method of charge stripping. This may be called the 'reverse polarity charging'. The physical basis of this method is to use charged particles of polarity opposite to that acquired by the particles with the aid of the setup shown in Figure 2. As has been mentioned earlier, a plot of U_m and U_r appears to show a hysteresis behavior. In this method of charging, the accumulated charge reduces with pressure in both bare and coated electrodes as shown in Figures 13(a), (b), and (c) and Figures 14(a) and (b).

A similar effect can be observed when bare and coated electrodes are compared at a constant working pressure, Figures 13(a) and 14(a) and 13(b) and 14(b). Thus the particles require higher lift-off voltages to reach the threshold value of the charge, because the area enclosed by the loop can be shown to be proportional to the charge and hence the energy of the particle. A similar hysteresis behavior is exhibited with air at atmospheric pressure as shown in Figure 15. Hysteresis under similar experimental conditions is observed with copper particles also.

5 CONCLUSIONS

In summary, the measured lift-off voltages seem to be independent of the electrode systems in question. The induced surface charge on the particle using prolate ellipsoidal approximation developed and based on the proposed model compares well with existing models. The lift-off forces estimated by the proposed model are in good comparison with those obtained with Felici's formula and the available data. The lift-off voltage levels are accentuated considerably when both electrodes are coated with a dielectric, in comparison to only the enclosure being coated, and to the case of bare electrodes. The reverse polarity charging method has a considerable advantage over the dielectric coating method in that the particles are passivated to much higher voltage levels. A similar effect is observed with coated enclosures also with the new technique. Better performance could be expected if the technique is used in conjunction with a coated enclosure. The area of the hysteresis loop is proportional to the charge and hence the energy, successively diminishes with pressure with both bare and coated enclosures, requiring higher lift-off voltages.

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