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THEORITICAL AND EXPERIMENTAL MODEL FOR PARTICLE INITIATED BREAKDOWNS IN GIS

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Abstract

Inadvertent failure of gas insulated system such as high voltage GIS is traced to a freak mechanism, in particle – induced breakdown. While conducting (metallic) particles cause a direct breakdown of the gaseous insulation due to a high degree of non-uniformity of electric fields surrounding them, dielectric (insulation) particles give rise to disruptive discharges due to surface charges acquired by them in the strongly divergent electric field in their vicinity. The deleterious effects of particles are too well known to be enumerated. Since it is not always possible to fabricate GIS without parasitic floating and fixed particles, and scavenging the particles bordering on microscopic dimensions is very difficult, study of the particle aided breakdown study acquires particular significance in GIS. The effect of particles of either kind being the same; the reduction in the dielectric strength of the system, every effort should be made to either prevent outages due to them or workout means of stabilising the system in their presence. The present paper, attempts to make a small contribution in this direction.

Introduction

Fully enclosed gas insulated modular substations (GIS) for medium voltages is known to offer a variety of advantages over conventional systems. The more important among them are the compact size, easy operability, and near maintenance free operation . Notwithstanding these advantages GIS suffer from inherent disadvantages such as, their proneness to electrical breakdown even around operating voltages due to metallic particles which are inadvertently present in them. Further, the medium there-in being SF6, a gaseous dielectric of choice, there are problems associated with the toxic by-products of the gas, formed during an electrical breakdown, either partial (pd) or complete. This is further accentuated in the presence of minute quantities of moisture in any form.

It should therefore be the endeavor of GIS designers to try and workout reliable operating conditions to mitigate this process. While it is almost impossible to preclude completely, the incipient breakdown it should at least be ensured that no extraneous breakdown occurs in the medium owing to causes other than the high electric field near the high voltage conductors.

The mid gap breakdown in GIS is almost always either due to conducting/dielectric particles. Free particle aided breakdown control, is usually achieved by either relieving the electric stress at different points in the medium by suitable methods or restricting the particles to stay put on the walls of the enclosure which is at zero potential. Under such conditions the lift-off voltages for the particles would be much higher than the normal operating voltage and the particles do not migrate towards the high voltage electrode thereby avoiding incipient breakdowns. The movement of metallic particles under the action of an electric field is also controlled by the medium, its density and there is sufficient background literature [1] which deals with these aspects.

Several aspects need consideration in the study, the more important among them being, the size and geometry of the particles, their nature (conducting or dielectric), position with respect to the high voltage electrode (fixed or floating), initial orientations and effect of the medium in which they exist. The dynamical aspects of particles like, their motion in an electrical field controlled by viscous drag of the medium and their effective mass need to be taken account of. Although extensive literature on the breakdown of gaseous medium is available, interaction of particles and electric effects on the reduction in breakdown strengths, with all the details mentioned above appear to be scanty.

In the present work the authors present a phenomenological model for the dynamics of metal particles having prolate spheroidal shape, and the equation of motion of particle takes into account the characteristic of the particle itself, electric field seen by the particle, and physical parameters of the medium . The paper also provides some experimental results that stimulate the processes during normal operation.

Dynamics of a conducting particle in an electric field

A stationary but free particle in an electric field acquires a net charge proportional to its area of projection in the direction of the field and is approximated by the equation

$$Q = 2\pi r l \, \varepsilon_o \, E(t) \quad \text{------ (1)}$$

Here, it is considered that the particles are a short cylinders of radius r, length l in their initial positions. Ignoring the non-uniformity of the field in the neighbourhood of the particle, the Maxwell force acting on the particle trying to disturb, or lift it can be written as;

$$F_d = E(t)\,Q \qquad \ldots (2)$$

In the absence of other restoring factors, such as the viscous forces, equation of motion of the particle of mass m under a gravity g can be written as;

$$m\,\ddot{x}(t) = F_d - mg \qquad \ldots (3)$$

Where g is the acceleration due to gravity. The equation (3) should be modified to take into account the viscous drag in the course of its motion towards the region of maximum field;

$$m\,\ddot{x}(t) = F_d - mg - \text{(a force proportional to the square of the velocity)} \ldots (4)$$

$$m\,\ddot{x}(t) = 2\pi rl\,\varepsilon_o\,E^2(t) - mg - k\,[\dot{x}(t)]^2 \ldots (5)$$

where $\ddot{x}(t)$, the vector acceleration can be obtained from (3) and treating this to be a function of E(t), equation (5) can be solved. But in practice equation (5) is rather complicated as E(t) is a function of the space co-ordinates and depending upon the geometry of the system in question, the solutions would be very involved. Also, if E(t) is of the form $E_0e^{j\omega t}$, the particle motion follows a sinusoidal variation and it executes a forced oscillatory motion[1].

In continuation to the particle motion what is interesting, in GIS, is to know whether or not a breakdown occurs, or alternatively, would there be a pre-breakdown (corona discharges)? This is determined by the actual field seen by the particle and not E(t). A field correction factor (enhancement factor) of 1.5–5 or more have to be applied in the presence of the particle depending upon the shape of the particle and its projection in the direction of E (t).

Experimental

A model GIS chamber was designed and fabricated in the laboratory for conducting a series of experiments on particle lift off and movement.

The h.v. source consisted of a 220V/115 kV, 10 kVA shielded, pd free test transformer. A 50/100 MΩ was used for limiting the current. Voltage was measured using a test (bleeding) coil connected to the primary of the transformer and duly calibrated.

The high voltage and earthed electrodes were both made of aluminium with edges rounded off to avoid incipient corona and other edge effects and the surface polished. The inter-electrode gap distance was adjustable between 0.0-8.0cm. The h.v. electrode was connected to the external circuit through the epoxy bushing fixed to the top flange of the test chamber.

The maximum voltage was restricted to 100 kV and pressure to 0.5 Mpa. Only free metallic particles lying on the earthed electrode have been considered for investigation, as they appear to be more critical in reducing the dielectric strength of the gas phase in GIS. The particles used were aluminium of dia.0.24mm, and copper of dia.0.22mm and the lengths varied from 5-20mm. The test chamber was evacuated to rotary vacuum ≈ 10^{-2} torr and dry nitrogen was admitted with flow rate adjusted to the required value and as the pressure stabilised, voltage was gradually applied to the electrodes. The lift off voltages were recorded for each type of particle. At least ten measurements per sample set were made.

Two different electrode systems were used in the series of experiments. In the first system, the ground electrode was made into a hollow split-cylindrical formation, while the h.v electrode was in the form of a hollow thick walled cylinder with re-entrant edges to avoid corona Fig.1(a). The second electrode geometry consisted of Rogowski profiled electrodes as shown in Fig.1(b).

Results and Discussion

The one dimensional equation, Eqn.(5) can be modified thus;

$$\ddot{x}(t) = k_1E_{rms}^{\,2}(t) - k_2\dot{x}^2(t) - g \qquad \ldots (6)$$

where the constants k_1 and k_2 are functions of the physical dimensions and the material density of the particle, and the fluid medium respectively.

As the particle just lifts up, the drag force experienced by it is negligibly small and hence the Eqn.(6) may be reduced to;

$$\ddot{x}(t) = k_1\,E_{rms}^{\,2}(t) - g \qquad \ldots (7)$$

Solution of this equation for different synthesised values of electric field expectedly yields curves as shown in Fig.2. for different diameters of a given density of the material of the particles. The solution to (7) gives the instantaneous positional acceleration at any time t due to gravitation. Particles become erect and then lifts off from the ground electrode. This field, the lift off stress is observed to be invariant w.r.t. the properties of the fluid medium, its pressure, geometry of the electrode system and the length of the particle, but is a function of the projected area normal to the direction of the field and the particle material density.

To check the results of the model represented by Eqn.(7), a few planned experiments were conducted with aluminium and copper particles in nitrogen gas medium over a range of gas pressures.

In view of the complexities in modelling the 3-D field distribution for the electrode system in question in the presence of conducting particles, it was found that, reasonably good approximate values could be obtained using a 2-D formulation. Computer programmes (ex: FEM packages and MATLAB) for this purpose are therefore used in this work with some modifications. The presence of particles on the grounded electrode causes localised field distortion to a considerable extent. A field enhancement factor (η) between 1.5-5 is found to give the required correction under such circumstance. The actual field seen by the particles (depending on their shape and size) is therefore got by simple multiplication of the field and η. It was observed that the results of the experiment were in reasonably good agreement with the predicted values (Table I). This table also includes the data of other authors. An estimate of the magnitude of the force experienced by the particles during lift off as a function of length, has been obtained using Eqn.(8).

$$F_{ese} = 2 \Pi r l \varepsilon_0 E^2 .... (8)$$

This shows that the force is nearly a linear function of the length of either types of particles.
It has been stated elsewhere [2] that a dielectric coating on the electrode surface could greatly increase the lift off field. In order to continue this work, a series of investigations to understand this mechanism , four different dielectric coatings have been tried out viz., polypropylene, polythene, FRP and mylar. Table II show the results of this work. Here,

$$\alpha = \frac{\text{Lift-off voltage for coated electrode}}{\text{Lift-off voltage for bare electrode}}$$

The results show that there is indeed an improvement of about two times the lift off field compared to bare electrode. During the course of investigations, a few interesting observations were made. The presence of dielectric fibres floating in the inter-electrode region, under electric stress, tend to conglomerate and aid the rapid movement of the conducting particles into the high field region causing eventual breakdown of the space shortened by the fibre-bridge. The lift off voltage gets reduced considerably. The effect of coating on the ground electrode has a similar tendency as mentioned earlier by which the lift off fields are almost two times the value for the bare electrode. A second and more interesting feature of this investigation pertains to experiments consisting of dielectric coated electrode with deliberate punctures made on the coating, so as to expose the electrode. It was observed that particles situated around the site of the puncture, lift as if they are on the virgin electrode.

Conclusions

Based on the current study, the following tangible conclusions can be drawn.

1. Lift - off fields are determined by the density of the particle material and area of projection normal to the direction of field.
2. Dielectric coated electrode seem to offer a decided advantage in that, increase in the lift off fields of the conducting particles. It is surmised that spacers of selected dielectric materials might help in restricting the movement of the conducting particles.
3. Presence of fibrous contaminants drastically reduce the lift - off voltages of the conducting particles, which could be increased with coated electrodes.
4. Lift - off voltages/fields are dependent on pressure with coated electrodes ,unlike the bare ones.

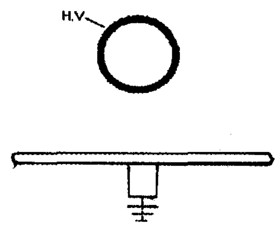

Figure.1(a) Electrode Type I

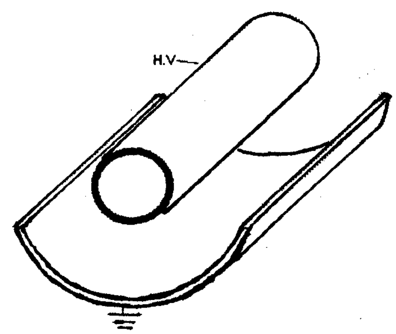

Figure.1(b) Electrode Type II

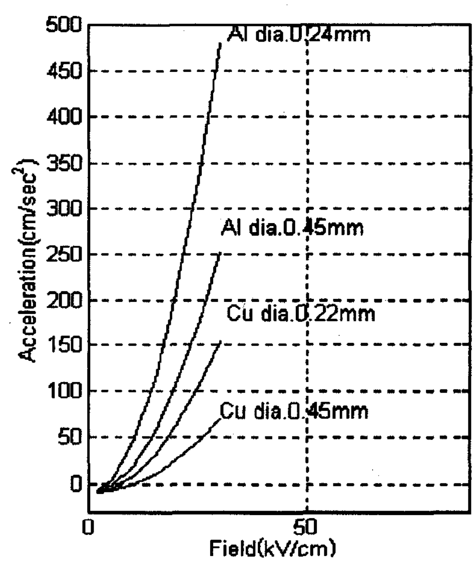

Figure. 2 Particle Lift-off fields from model Eqn.(7)

Table I A Comparison of Experimental and Calculated particle lift-off fields using different electrode geometries

Electrode	Dia. mm	Medium	Calculated E_L kV/cm	Experimental Data E_L kV/cm	
Parallel-Plane	Al 0.45	SF_6 Air N_2	5.82 5.82 5.82	5.5 5.2 5.4	[1]
	Do	SF_6	5.82	5.6	[1]
	Cu 0.45	Air SF_6	10.5 10.5	9.1 8.6	[1]
Co-axial 250/76 mm	Al 0.45	Air	5.82	6.3 7.2	[1] [4]
	Cu 0.45	Air	10.5	9.2	[1]
Co-axial 167/57 mm	Al 0.5	SF_6	5.82	5.6	[1]
	1.0		8.67	7.1 7.6 10.2	[3] [4]
	1.4		10.2	8.0 8.9	[3]
Type I	Al 0.24	N_2	4.24	4.4	
	Cu 0.22		7.36	7.1	
Type II	Al 0.24	N_2	4.24	4.1	
	Cu 0.22		7.36	7.5	
			$V_{Lift\text{-}off}$ kV_{rms}	$V_{Lift\text{-}off}$ KV_{rms}	
Co-axial 250/76 mm	Al 0.45	SF_6	87	90	[1]
		N_2	87	99	

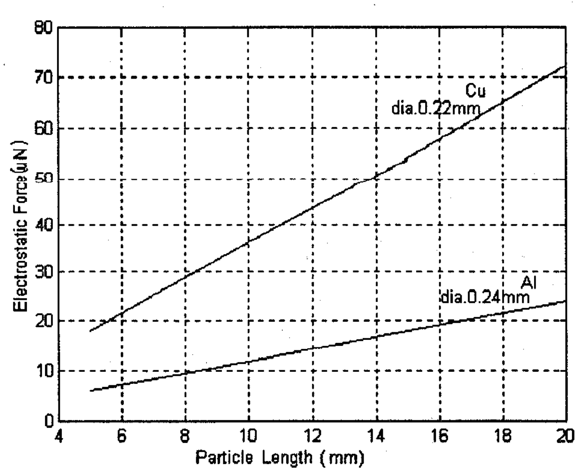

Figure. 3 Electrostatic Force on the particle at Lift-off

Table II A comparison of Lift-off Voltages for bare and coated electrodes

Electrode Condition	Type	Pressure Mpa	V_L kV Al	V_L kV Cu	α Al	α Cu
Bare	I	0.1 0.3 0.45	32 35 33	35 40 39	- - -	- - -
Bare	II	0.1 0.3 0.45	36 34 35	37 44 48	- - -	- - -
Coated						
Polythene	II	0.1 0.3 0.45	43 58 64	53 64 73	1.2 1.7 1.9	1.4 1.6 1.8
Polypropylene	II	0.1 0.3 0.45	36 62 75	44 55 75	1.1 1.9 2.2	1.1 1.4 1.9
FRP	I	0.1 0.3 0.45	46 57 64	58 68 80	1.3 1.6 2.1	1.5 1.7 2.0
Mylar	II	0.1 0.3 0.45	47 53 62	43 80 86	1.4 1.3 1.8	1.1 1.5 1.6

Medium – Nitrogen   Gap – 4.0cm

References

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