INFLUENCE OF PARTICLES ON DC DIELECTRIC PERFORMANCE OF INSULATING GAS (SF_6)

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Abstract: The main focus of this paper is on the contamination of a gas-insulated system with particles under DC conditions. Particles in a gas enclosure are unavoidable when a GIS or GIL is constructed. This is a well-known problem and requires great attention to it, because particles can have a great influence on the electrical field and thereby deteriorate the dielectric strength of the gas.

Substantial differences between AC and DC voltages can be recognized, which influences the particle behaviour strongly in respect of acting forces and partial discharge activity. Therefore it is essential to understand which effects have influences on particles in electrical static fields. Also the geometric form of the particles is crucial, since with increasing aspect ratio the inhomogeneous field distribution increases as well.

The experiment set-up was basically a test-vessel with a homogeneous electrode arrangement. With this test vessel, the basic behaviour of selected particles in a DC field could be investigated with a CCD-camera. Numerous parameters, such as distance between electrodes, the size and shape of the particles and the pressure of the insulating gas were tested. Changing parameters results in different particle behaviour.

Two basic movements were observed: namely the Bouncing- and the Standing-Motion. Both types of motion have been extensively studied in this work. In addition the lift off field strength of the particle was calculated and a statistical evaluation was undertaken as well to determine the average value and the variance. The objective of this work was to investigate and determine experimentally the behaviour of particles. Against disturbing influences caused by conductive particles, measures should be developed to neutralize them.

1 INTRODUCTION

Compressed gas filled systems are highly sensitive to free or fixed conductive particles. These particles may result from mechanical abrasion, vibrations or damages during assembly of the enclosure. Recently, interest in particles under high DC-stress has been growing because HVDC transmission is getting more important. Because particles behave under DC-stress differently from AC-stress it is essential to understand which effects have forces and influences on particles in an electrical static field. Great attention is also paid to insulators, their charging behaviour and the accumulation of room charges. The main focus of this study is on contamination by conductive particles in gas-insulated systems. This is a well-known problem and requires high attention, because they can have a great influence on the electrical field and thereby deteriorate the dielectric strength of the gas. Besides the influence of moisture, four important types of insulation defects are known [1].

The typical defects are:

1) Protrusions,
2) Particles fixed to an insulator surface,
3) Free moving particle
4) Electrically floating parts

This work focused on free moving particles because this is the defect that occurs most often in GIS/GIL and it is the most dangerous also [2].

1.1 General

Basically, a distinction is drawn between a stationary and a movable particle. Depending on the accumulated charge of the particle and the applied electric field, an electrostatic force acts on the particle. The charged particle will lift as soon as the electrostatic force exceeds the gravitational force. Under the influence of the electric field the particle is moving inside the enclosure. Reach a particle the surface of the conductor, it is possible that it can be attached to it and act as a stationary impurity which can cause an electrical breakdown. A free conducting particle resting in contact with an electrode of an energized system is a localized perturbation which acquires charge and distorts the electric field. The shape, location, and orientation determine the induced charge distribution [3]. One consequence of this charge is a net electrostatic force on the particle in a direction away from the electrode. The force can be determined by integrating the product of surface charge density times electric field vector over the entire particle surface. A particle of mass m resting on an electrode will thus be elevated when the electric force exceeds gravitational and contact forces and will accelerate, $\vec{a}$, according to the force equation:

$$m\vec{a} + \vec{F}_{elect.} + \vec{F}_{grav.} + \vec{F}_{drag} = 0 \tag{1}$$

It is also assumed that the particle impacts on both the inner and outer electrodes are not perfectly elastic. The restitution coefficient R_c, for both the inner and outer electrodes, is defined as the modulus of the ratio of the particle velocities after and before impacts. The electric force F_e = qE, where the electric field E is a function of both the time t and particle position x, and the particle charge q depends on the particle dimensions (length l_w, and radius r_w,). The lifting charge for a standing Particle is given by [4].

$$q_1 = \frac{\pi\varepsilon_0 l_w^2 E_1}{\ln\left(\frac{2l_w}{r_w}\right) - 1} \tag{2}$$

Where ε_0 is the permittivity of free space. For a lying particle the equations is:

$$q_1 = \pi\varepsilon_0 2 r_w l_w E_1 \tag{3}$$

Hence the electrical field strength is for a lying particle [5]:

$$E_2 = \sqrt{\frac{2(r_w)\rho g}{2{,}86\varepsilon_0}} \tag{4}$$

And for a standing particle:

$$E_2 = \frac{ln\left(\frac{2l_w}{r_w}\right)-1}{2}\sqrt{\frac{(2r_w)^2\rho g}{\varepsilon_0 l_w (ln\left(\frac{l_w}{r_w}\right)-0{,}5)}} \tag{5}$$

The particle behaviour is influenced by the direction of forces acting on the particle.

Although the direction of the electrical forces, such as coulomb and electrical gradient force, depends on the electrical field distribution in the gap, the direction of the gravitational force always points to the bottom. When the inner conductor has an inclination relative to the outer conductor, the electrical field distribution on the electrode surface is nonuniform. In such nonuniform electric field gaps, conducting particles are acted upon by Coulomb force in the direction of the electric lines of force and by electrical gradient force in the direction towards the higher electric field region [6].

1.2 Initial Motion

Due to a change in the charge magnitude and distribution, the electrostatic force on an elongated particle is greater when it stands vertically than when it lies flat, thus the lift-off field for a particle lying flat is greater than when it stands vertically. The difference increases with increasing particle length-to-radius ratio. As a consequence of this difference, in the absence of corona, an elongated particle such as a wire which is lying on an electrode will not only be elevated at the lifting field value, but will also have a significant net force immediately moving it into the gas gap. In addition, the greater force experienced by a particle which moves into a vertical position causes a hysteresis effect. That is, after motion has begun the field required for the particles to fall down and stop moving can be several times lower than the original lifting voltage [3].

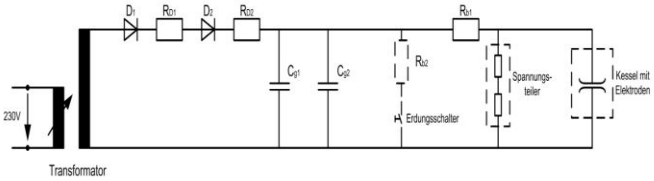
1.3 Motion under DC-Conditions

After a particle is elevated its motion is mainly dependent on the charge it carries and the applied field in its immediate vicinity, the electrostatic force being simply qE. For a DC field a particle in the absence of corona is driven across the gap until it strikes the opposite electrode where it is oppositely charged and driven back to repeat the motion and oscillate between the electrodes. Inertial and viscous drag forces influence the velocity attained during a crossing and while small particles can be expected to attain a steady state “drift” velocity, the more dangerous large particles can still be accelerating at impact. The driving forces for such oscillations stem from the action of the electric field on the electrically charged particle and it can be observed for all types of particles under DC-conditions.

2 EXPERIMENT SET-UP

The experimental set-up was undertaken on a small scale with a modular component system, which consists of a transformer of 100kV as a power supply, diodes for rectifying the AC voltage into a DC voltage, a capacitor for smoothing and a resistor to limit the current at an event of breakdown. This circuit (**Figure 1**), was applied on an 80-liter test vessel in which the investigations with the particles were carried out.

Figure 1: Equivalent circuit of the test set-up



A resistive voltage divider measured the applied voltage and for the PD measurement according to IEC 60270 a coupling capacitor was used. Furthermore a CCD-camera was installed to record the particle behaviour in accordance to the PD measurement. In the test vessel a Plate - Plate electrode arrangement was set up to gain a homogeneous field distribution. Before tests began the particle was placed in the middle of the bottom electrode. Conductive particles with different properties were investigated in order to determine dependencies of different influencing factors. These were:

- different materials, such as copper and steel
- different length: 2, 4, 6mm particles
- different shapes: elongated or spherical shaped
- different gas pressures
- different electrode distances: 10mm, 20mm

Sulphur hexafluoride (SF6) was used because of its good breakdown characteristics and for comparability with other investigations.

3 DETAILED INSTRUCTIONS

For determining the different parameters of the lift of field strength several cases were investigated. **Table 1** shows several particles of different forms, length, diameter and materials. Furthermore the electrode distance and the gas pressure were altered as well.

Table 1: Overview of investigations with different parameters.

		Particle Parameters			Test Vessel Parameters	
Test Series	Form of the Particle	Length [mm]	Diameter [mm]	Material	Electrode Distance [mm]	Gas Pressure [MPa]
1	Cyl.	2, 4, 6	0,26	Copper	9,6	0,1
2	Cyl.	6	0,26	Copper	9,6	0,3
3	Cyl.	6	0,26	Copper	19,6	0,1
4	Cyl.	4	0,4	Copper	9,6	0,1
5	Cyl.	4	0,3	Steel	9,6	0,1
6	Sph.		2	Stainl. Steel	9,6	0,1

Two different movements could be observed which were dependent on the applied voltage:

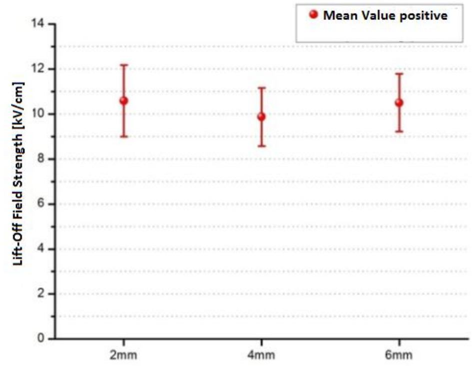
- Standing-Motion
- Bouncing-Motion

When the voltage arose from zero to a certain value, due to the electrostatic forces the particle started to lift-off and tried to align along the field lines. This movement is called standing motion. In this case the particle discharges itself by having partial discharges at its tip, but recharges by getting charges from the electrode. Thereby the force of the partial discharges at its tip makes the particle to be upright on the electrode and move around on the surface of it. When the voltage decreases there is not enough force from the partial discharges to keep the particle on the ground and it starts to bounce between the electrodes, this is the so called bouncing motion. We were surprised to discover this because it was expected that after the standing motion the particle gets into the bouncing motion when the voltage is increased.

3.1 Influence of the particle length on the lift-off field strength (test series 1)

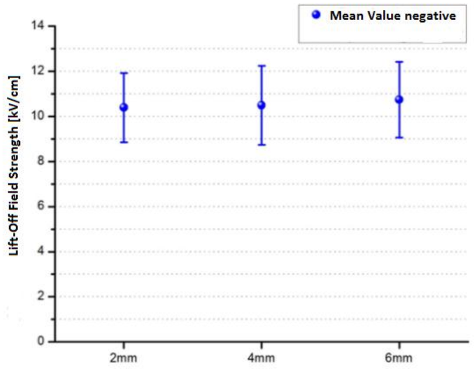
Figure 2 gives the lift-off field strength over different particle lengths at positive polarity,

Figure 2: Different particle length at pos. voltage



whereas **Figure 3** indicates the same particle sizes at negative voltage.

Figure 3: Different particle length at neg. voltage.

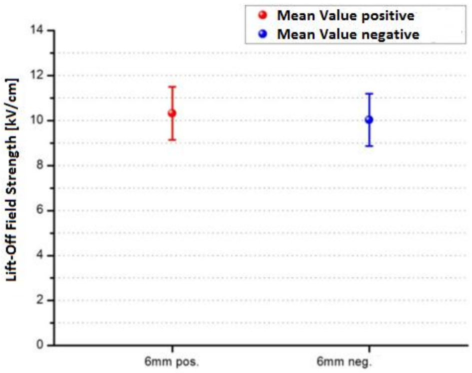


It is shown in both tables, that the lift-off field strength is nearly the same regardless the particle length and the polarity of the applied voltage. The values of the lift-off field strength differ little and come from inaccuracies of the measured voltage and particle length as well. The average value of both diagrams is 10,4 kV/cm.

3.2 Increasing the pressure of the insulating gas (test series 2)

With an increased gas pressure of 0,3MPa same experiment procedure with copper particles of 6mm length were carried out. Other parameters like electrode distance, particle diameter or the form of the particles were not altered. **Figure 4** shows the lift-off voltage of the particles.

Figure 4: Lift-off voltage of 6mm copper particles at 0,3MPa gas pressure.

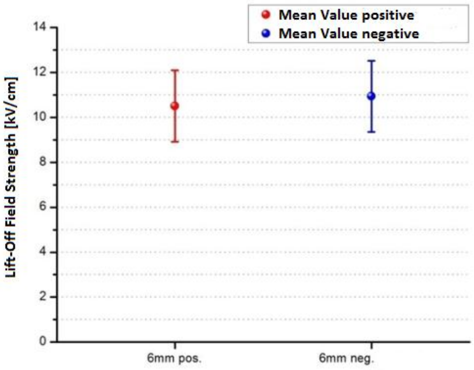


The lift-off voltage has not changed compared to lower gas pressure at 0,1MPa, but significant differences in the particle motion could be observed. Since there was a suppression of partial discharge due to higher gas pressure, the force of partial discharges on the particle is lower as well. Only bouncing motion was possible, hence the particle bounces between the electrodes after lifting off.

3.3 Increasing the electrode distance (test series 3)

If the electrode distance doubles the voltage as well has to be stepped up twice as much in order to get the same field strength. The length of the copper particles was 6mm, and their diameters were 0,26mm. The investigation was carried out at a gas pressure at 0,1MPa. **Figure 5** shows the lift-off voltage of the particles at the electrode distance of 19,6mm, which has also the same value as at an electrode distance of 9,6mm.

Figure 5: Lift-off voltage of 6mm copper particles at an electrode distance of 19,6mm.

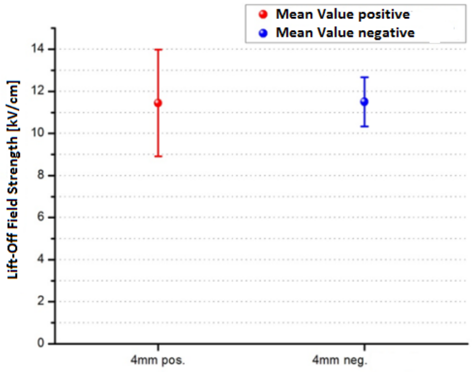


Differences in the particle motion could be noticed here as well. After standing motion when the voltage was decreased bouncing motion could observed at higher field strength than with a lower electrode distance. This can be explained by the ratio between particle length and electrode distance. When the particle stands on the ground of the earth electrode towards the HV-electrode at lower electrode distance the tip of the particle experiences a higher electrical field than at the greater electrode distance of 19,6mm. A lower electrical field on the tip causes less partial discharges and therefore a lower force on the particle which keeps it on the bottom electrode surface.

3.4 Increasing the diameter of the particle (test series 4)

According to the theory an increased diameter of an elongated particle leads to a higher lift-off field strength. A copper particle with a length of 4mm and a diameter of 0,4mm was chosen. The electrode distance was 9,6mm at a gas pressure of 0,1MPa. **Figure 6** indicates the mean value of the lift-off field strength of the particle which has an average lift-off field strength of 11,47kV/cm.

Figure 6: Lift-off voltage of 6mm copper particles with a diameter of 0,4mm.

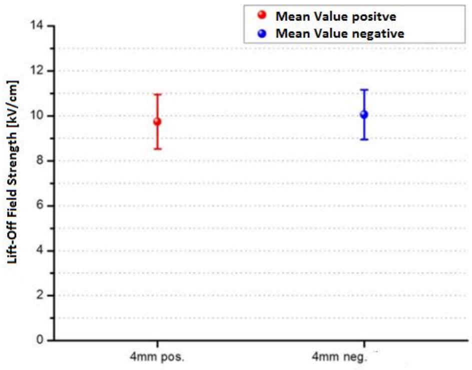


Compared to a particle with a diameter of 0,26mm its lift-off field strength has a value of 10,4 kV/cm and it is significantly lower than the lift-off field strength of a particle with a bigger diameter.

3.5 Particle of Steel (test series 5)

A further parameter that was changed was the material of the particle. Instead of copper, particles of steel were used. Also here, elongated particles of 6mm length and a diameter of 0,3mm were investigated at an electrode distance of 9,6mm and a gas pressure of 0,1MPa. **Figure 7** gives the mean values of the 6mm steel particles.

Figure 7: Lift-off voltage of 6mm steel particles at an electrode distance of 9,6mm.

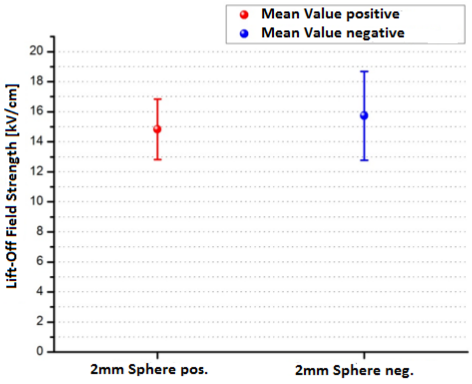


Also here the measured value of 9,9kV/cm matched quite well to the theoretical values of 9,62kV/cm, which deviates 2,9%.

3.6 Spherical particles of steel (test series 6)

Further examinations of 2mm spherical shaped particles of steel were undertaken as well. Here also, the electrode distance was unchanged at 9,6mm at a gas pressure of 0,1MPa. For a spherical particle only bouncing motion is possible. **Figure 8** gives the mean value of 14,4 kV/cm of the lift-off voltage.

Figure 8: Lift-off voltage of 2mm steel spheres at an electrode distance of 9,6mm.



Due to the impact energy the spheres remained longer in bouncing motion than the elongated particles even though the voltage was already switched off.

4 CONCLUSION

According to the theory, the lift-off field strength of an elongated particle depends on the relative density, the gravitational acceleration, the permittivity and the diameter. Different series of experiments were undertaken in order to determine the dependencies.

First we investigated copper particles of a length of 2mm, 4mm and 6mm and a diameter of 0,26mm. The gas pressure was 0,1MPa and the electrode distance was set at 9,6mm. No major differences between the particle lengths in lift-off field strength could be observed. This is in line with the theory.

A further investigated parameter to determine the particle motion was the gas pressure. Also here can be shown that the gas pressure has no influence on the lift-off field strength. But due to partial discharge suppression the bouncing motion was at a higher field strength than at a lower pressure.

When the electrode distance was altered the lift-off field strength remained unchanged as well, also here a different particle behavior could be observed. When the particle was in a standing motion and the voltage was decreased, bouncing motion began earlier at a higher voltage than at a smaller electrode distance.

Increasing the diameter of the particle to 0,4mm with 6mm copper particles at an electrode distance of 9,6mm and a gas pressure of 0,1MPa it could be shown that the diameter of the particle influences the lift-off field strength. A higher lift-off field strength was determined according to the theory.

A further aspect was the relative density of a particle. Instead of copper a steel particle was used to change its behaviour. Possibly due to a very similar density to copper particles no major differences could be observed.

The final test series investigated a spherical particle at an electrode distance of 9,6mm at 0,1MPa gas pressure. With this kind of particle only bouncing motion is possible. This particle behaviour is also in line with the theory and that bouncing motion persists for a longer time due to impact energy.

In contrast to other publications this work investigated the particle behaviour under DC conditions in a homogeneous field. Both polarities were applied to the particle and a key finding was that the particle at positive polarity moves at the surface of the bottom electrode whereas the particle at negative voltage moves at the surface of the upper electrode. This is because contrary charges attract each other. Since the partial discharge current is more negative, the particle always appears more positive charged compared to the negative (or grounded) electrode.

We only investigated copper and steel particles because they could reproduce easily. In a next step the influence of different particle materials such as aluminum will be investigated.

Furthermore the field utilization factor of a GIL is about 60%. Therefore a quasi-homogeneous electrode arrangement is required to investigate particle behaviour in a more practical way.

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