Investigations of conductive Particles in Gas Insulated Systems under DC-Conditions

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Gas insulated systems, have proven to be reliable for many years. But despite of a high availability some defects, in particular free moving particles can be very critical. Contamination with particles can result from mechanical abrasion or due to vibrations as well as the enclosures damages during the assembly. A further aspect is that power transmission with DC is getting more important. Therefore Gas Insulated Systems operated with DC will be required in the future. But particle behavior under DC-condition is much more different than under AC-condition. The aim of our investigations is a realistically determination of particle movement in a small scale set up with gas filled test vessel. An appropriate electrode arrangement was designed in order to achieve a similar utilization factor of a real size arrangement. To get an optimized field distribution, simulations by a FEM-program were undertaken as well as different electrode forms were used in the experiments. Experiments were carried out with different sizes of particles at different gas pressures with SF_6-gas. In order to get a correlation between particle movement and partial discharge activity, a camera was synchronized with the PD-measurement. Finally statistical evaluation of the lift-off field strength was made for both polarities.

I. 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 in a quasi-uniform field because this is the defect that occurs most often 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 $F_e = qE_0$, where the basic electric field E_0 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 acharge for a standing Particle is given by [4].

$$q = \frac{\pi \varepsilon_0 l_w^2 E_0}{\ln\left(\frac{2l_w}{r_w}\right) - 1} \tag{2}$$

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

$$q = \pi\varepsilon_0 2 r_w l_w E_0 \qquad (3)$$

The required electrical field strength for a laying particle to lift-off is [5]:

$$E_{lift-off} = \sqrt{\frac{2(r_w)\rho g}{2{,}86\varepsilon_0}} \qquad (4)$$

Where ρ is the mass density and g the gravitational constant.
And for a standing particle the required electrical field strength is:

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

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.

1.4 Particle Motion in a quasi-uniform Field

In this paper we will show the different behaviour of particles in a quasi-uniform electrical field. Investigations were undertaken in a radial field, which showed us that in general two different types of particle motions are possible and its behaviour is also 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. In this case the particle remains in a standing motion.
But when the applied voltage is lowered 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. This is quite surprising as it is assumed that the particle should bounce when the field strength is higher [7]. Another observation was that when it comes to the standing motion, the particle is found always at the more negative electrode. This means, the particle moves around at the bottom under positive voltage and remain in standing motion under the surface of the upper electrode under negative voltage. In the case of a uniform field there are no differences in partial discharge activity between positive and negative polarity [7]. In contrast to a radial field distribution were the field strength at the inner conductor is much higher than at the enclosure, the partial discharge activity at negative voltage must be much higher because of particle movement at the inner conductor. This was our intention to do some investigations in a more practical way.

II. Experiment Set-up

The experimental set-up was undertaken on a small scale with a modular component kit, 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.

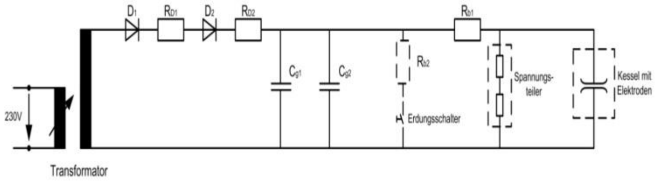

Figure 1: Equivalent circuit of the test set-up

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 special electrode arrangement was set up to get a similar utilization factor as of a real tubular transmission line. The design of the electrode arrangement is basically a segment of a coaxial arrangement and rescaled to one third of it (**Figure 2**).

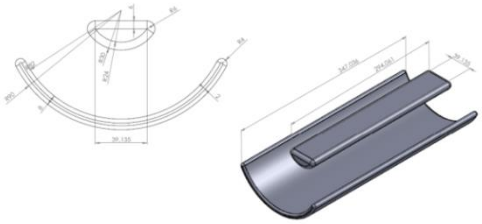

Figure 2: Design of the electrode arrangement

Hence the radius for the HV-conductor is 30mm and 82mm for the enclosure. For the required field utilization factor η of 0.57 a gap of 52mm is needed. The utilization factor can be determined by the ratio of E_0/E_{max}. Whereas E_0 is the applied voltage divided to the gap distance and E_{max} the maximum occurred electrical field strength. 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 length: 2, 4, 6mm particles
- Different gas pressures

The tested particles were elongate wire particles of copper with a diameter of 0.25mm. Sulphur hexafluoride (SF_6) was used because of its good breakdown characteristics and for comparability with other investigations.

III. Results

To achieve a certain utilization factor a sphere plate electrode arrangement is also possible. For this approach a certain sphere diameter should be chosen and the appropriate gap can be calculated. But it turned out soon that this electrode arrangement did not correspond to a comparable coaxial arrangement, because the utilization factor η of 0.57 can be found only in one point. With the new electrode design according to Figure 2 big improvements were achieved. This means that the particle finds everywhere the same electrical field strength at an applied voltage.

Once the electrode arrangement was designed, wire particles of 2mm, 4mm and 6mm were tested. A particle was set onto the bottom of the grounded electrode before the DC-voltage was ramped up until the lift-off field strength of the particle was reached. Figure 3 shows the mean values with the confidence interval of the lift-off field strength of different particle lengths. For the statistical evaluation a minimum of twenty repetitions were carried out. For 2mm particles at positive polarity no reliable values could be measured because the size of 2mm was too small for a proper observation.

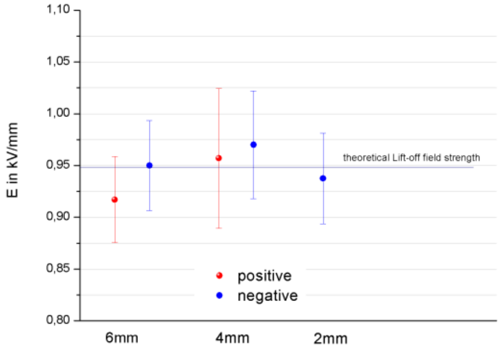

Figure 3: Lift off field strength of different particle sizes

A further parameter what was changed were different gas pressures at which the lift-off field strenght was investigated. First experiments were undertaken at 0.1MPa with both polarities. Further investigations were carried out at higher pressures such as 0.2MPa and 0.4MPa. In figure 4 it can be seen that for a 6mm copper particle with a diameter of 0.25mm no major differences can be seen between different pressures and polarities.

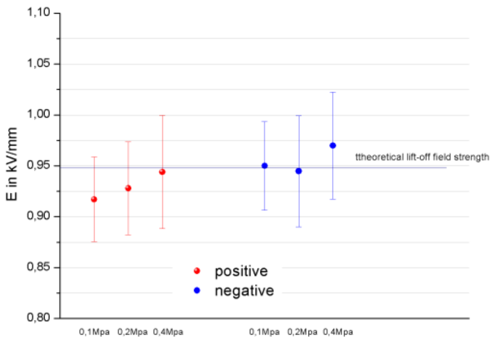

Figure 4: 6mm particles at different pressures

In contrast to the lift-off field strength partial discharge activity in a quasi-uniform field behaves different between both polarities. As previous work in uniform fields has shown [6] metallic particles always move to the more negative electrode. Since in a uniform electrical field the field strength distribution is everywhere constant, the magnitude of the partial discharges do not differ from the other polarity. But in a quasi-uniform field such as a coaxial arrangement, the maximum field strength is at the HV-electrode much higher than at the surface of the grounded electrode. Since here as well particles move to the HV-electrode at negative polarity, partial discharge activity is higher as well. Table 1 shows the result of measured partial discharge values at ±80kV with different particle sizes.

Particle size [mm]	Partial Discharge at positive Polarity [pC]	Partial Discharge at negative Polarity [pC]
2	–	22
4	5,32	40
6	12	73

Table 1: Values of partial discharges at different polarities

It can be clearly seen that the values at negative voltages are much higher than at positive polarity, because of the particle motion in a higher electrical field.

IV. Conclusion

Investigations of particle behavior were undertaken with an optimized electrode design for small scale experiments, which should be comparable to a gas insulated tubular transmission lines. The geometry was resized to a third of the real design and only a segment of the coaxial arrangement was taken. With this design the same utilization factor η could be gained. Tests of lift-off field strength with different particle sizes show that there were no major differences between polarities nor to different particle length or pressures. This is in accordance to the theoretical lift-off field strength which is expressed to equation (4) and to previous investigations.

By contrast, major differences could be observed in terms of partial discharges. Particle motion is always at the more negative electrode, this means that at positive polarity the particle movement is at the grounded electrode and at negative polarity at the HV-electrode.

This is because the particle discharges itself by negative charges steadily, therefore the particle is always more positive charged than the more negative electrode. Since oppositely charges attract each other the particle is always be found at the more negative electrode.

But there is a higher electrical field strength, therefore partial discharge activity is more harmful than at positive polarity.

REFERENCES

[1] 15.03, CIGRE Working Group, „Long term performance of SF6 insulated systems.,“ CIGRE Report 15-301, Paris, 2002.

[2] 15.03, CIGRE Working Group, „Diagnosis Methods for GIS Insulating Systems,“ CIGRE Session 1992, paper 15/23-01, Paris, 1992.

[3] C. M. Cooke, R. E. Wootton, A. H. Cookson, „Influence of Particles on AC and DC Electrical Performance of Gas Insulated Systems at Extra-High-Voltage,“ IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, no. 3, 1977.

[4] K. S. Prakash, K. D. Srivastava, M. M. Morcos, „Movement of Particles in Compressed SF6 GIS with Dielectric Coated Enclosure,“ IEEE Transactions on Dielectrics and Electrical Insulation, 1997.

[5] Wohlmuth, M., „Einfluß beweglicher Partikel auf das Isolierverhalten gasisolierter Schaltanlagen.,“ TU-München, 1992.

[6] S. M. El-Makkawy, S. S. Dessouky, Waleed M. El-Zanaty, „A Study of the Particle Movement in Diverging Electrodes under DC Voltage in GIS.,“ IEEE, 2004.

[7] T. Berg, C. Müller, T. Malcher, M. Muhr, D. Imamovic, „Influence of Particles on DC Dielectric Performance of Insulating Gas (SF6),“ ISH, Seoul, 2013.