The Influence of Free Moving Particles on the Breakdown Voltage of GIS under Different Electrical Stresses

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***Abstract*—Although Gas Insulated Switchgears (GIS) have proven to be reliable for more than forty years, some failures have been reported. In particular, failures due to free particles have been a serious problem for years. The presence of these particles results in a local field concentration which influences the insulation medium and can result in a breakdown.**

In this paper, the influence of free moving particles on the breakdown strength in GIS under AC voltage, AC + LI (Lightning Impulse) overvoltage and AC + VFTO (Very Fast Transient Overvoltage) has been investigated with the maximum amplitudes of 1.2 p.u., 3.5 p.u. and 2.1 p.u. respectively. Elongated metallic particles with the lengths ranging between 2 to 30 mm have been investigated.

The results show that particle with a length of 10 mm and longer were dangerous to the insulation system under continuous operating AC voltage.

A breakdown area has been distinguished based on the particles length under AC + LI and AC + VFTO. Particles of 15 mm long were found to be critical under AC + LI, while under AC + VFTO, the 30 mm particle was critical. However, due to limitations in the test setup, the voltage level for LI was 1.4 p.u. higher than for VFTO.

The particles detectability have also been investigated by means of partial discharge (PD) measurements of different methods:

- **the conventional method (IEC 60270)**
- **the UHF method**
- **the acoustic method**

The PD results have shown that some defects can cause a PD level higher than 10pC. In general, such PD levels are detectable by all methods.

Keywords: Free moving particles, VFTO, PD measurement, GIS

I. INTRODUCTION

GIS has been giving a consistently high performance for more than forty years, however some failures have been reported. One of the important problems is due to the presence of metallic particles inside of the GIS compartment. The particles can give rise to field non-uniformities, which can reduce the breakdown strength. The situation becomes even worse when the particle is attached on the spacers.

CIGRE report 15/23-01 mentioned that the failures caused by free particles and foreign bodies represent 20% of the total distribution of defect types leading to GIS failures [1]. The origins of the particles are twofold:

- they may remain after GIS erection because they were not detected by onsite tests, or
- they can be produced after the on-site tests, for example by contact wear or by sparking between loose shields

Regarding to these situations, the study of particles influence in GIS operation is very necessary. In this paper, the particles influence to the breakdown voltage of GIS insulation has been investigated under different voltage stresses: AC voltage, AC + LI and AC + VFTO.

II. DIFFERENT ELECTRICAL STRESSES IN GIS

The mobile particles can become dangerous under electrical stresses. In particular, they can start jumping under AC voltage resulting in a reduction of the breakdown strength. During the GIS operation, different electrical stresses occur in the system [2]:

- AC continuous power frequency voltage.
- Temporary overvoltages (TOV) due to the load rejection, earth faults and resonance phenomena.
- Transient overvoltages including the slow-front, fast-front and very fast transient overvoltages.
    - Slow-front overvoltages arise from faults, fault clearing as well as from damped lightning strokes on distant overhead lines.
    - Fast-front overvoltages which originate from e.g. lightning strokes near the GIS. The front-time of the surges is in the range of one to few micro seconds.

- Very fast transient overvoltages (VFTOs) which occur during the switching process of disconnector and circuit breakers. Their front-time is in order of few nanoseconds.
- DC voltage stresses due to trapped charges in some particular GIS segments.

The summary of the voltages is presented in figure 1 based on the amplitude and time duration:

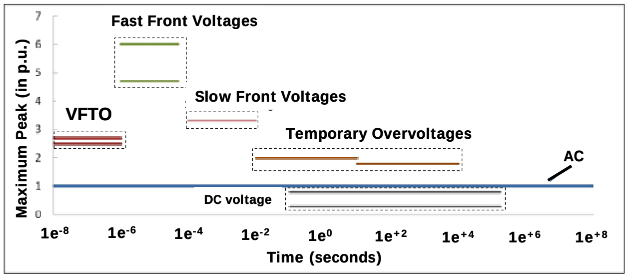

Figure 1. Different Voltage Stresses during the Operation of GIS [2]

In this paper, the discussions have been limited to AC voltage, AC + LI overvoltage and AC + VFTO.

III. GIS Test Set Up

Two GIS test setups have been used during the investigations. The first test setup was built in the high voltage (HV) laboratory of Delft University of Technology to perform the tests with AC voltage and AC + LI. The second test setup was built in HV Laboratory of Stuttgart for the investigation with AC + VFTO.

For the test setup used in Delft, the outer/ inner conductors were made of aluminum and have a radius of 150/35 mm. The inner electrode was connected to the voltage source via a gas filled (Nitrogen at 2 bar) bushing. The enclosure was equipped with a small window which has been used for measurements and observation purposes. (see figure 2 - left)

A camera connected to a video display was placed in front-of the window to observe the particle movement during the investigation under AC voltage. Sulphur Hexaflouride gas (SF_6) at 4 bar was used to insulate the high voltage conductor.

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Figure 2. GIS Test Setups Used in the Experiments, in TU Delft (left) and in TU Stuttgart (right)

The GIS test setup used in Stuttgart has a ratio of outer/ inner radius 250/80 mm. The center conductor was made of aluminum, except for the sparking gap where two copper sphere electrodes were used with adjustable distance gap. The VFTO was generated at this point.

Observation windows were placed at the top of the spark-gap and the particle compartments. The total length of the test setup was 7.5 m. The surge from the impulse generator was coming into the compartment via a polymer bushing as shown in figure 2 (right).

The maximum voltages that could be generated in these setups were the following:

AC voltage : 1.2 p.u.
AC + LI : 3.5 p.u.
AC + VFTO : 2.1 p.u.

IV. Particles Selection, Shape and Dimension

The free particles might be originated from different sources during the manufacture process, maintenance or operation of GIS. In the experiments, elongated cylindrical metallic particles of 2-30 mm length were used. The reasons were the following:

- The cylindrical metallic shape is the most found particle in practice. [3]
- The field enhancement at the particle tips are considered to be the most dangerous to the insulation system. [3]
- In order to make a relation between the particle length and the electric field stresses, particles with different lengths have to be investigated.

An example of a particle used in this work is given in figure 3. During the experiments, this kind of particles were placed inside of the compartment and subjected with the voltage stresses.

Figure 3. An example of aluminum particle used during the investigation under AC Voltage

V. Experimental Results

A. Investigation under AC Voltage

Under AC voltage 1 p.u., it is possible for a defect to start moving, or flying and getting attached to the spacer and trigger a breakdown. Therefore, to prevent a breakdown during the investigation, the voltage was reduced as soon as the particle started to jump.

In this study, the breakdown criteria under AC voltage was determined as the condition when a particle started flying and getting closer into the inner conductor. Based on the experiment in the laboratory the particle with the minimum length of 10 mm was able to fly after the introduced of vibration at the enclosure. Therefore, the critical particle length under AC voltage was 10 mm.

B. *Investigation under AC + LI Overvoltage*

Under AC + LI, the worst situation occurs when the lightning strikes the GIS at the moment the particle gained its maximum jump height. Further investigations have found the breakdown was easier with the negative lightning polarity. However, it is difficult in reality to simulate this situation in the experiment with the superimposed overvoltage. Therefore, a different approach had been performed by hanging the particle to simulate the jump as shown in figure-4:

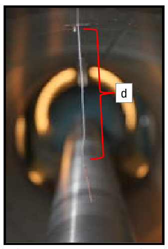

Figure 4. The hanging particle to represent the height of the particle jump.

The particle was placed at a certain distance that represented the maximum height of the jump (d). The value of d was found by solving the second order equation consisting of different forces acting on the particle during its travel [4]:

$$m.\ddot{y} = \frac{\pi.\varepsilon_o.\ell^2.E(t_o)}{ln\left(\frac{2\ell}{r}\right) - 1}\left(\frac{\hat{V}.sin\,\omega t}{[r_o - y(t)].ln\left(\frac{r_o}{r_i}\right)}\right) - m.g - Fd \quad (1)$$

where:

m	mass of the particle (kg)
ε_0	permittivity constant
ℓ	particle length (m)
r	radius of the particle (m)
$E(t_0)$	Electric field strength (V/m)
$V.sin\omega t$	Voltage applied (Volt)
r_o	outer radius of GIS (m)
r_i	inner radius of GIS (m)
π	pi = 3.14
F_d	drag force
$\ddot{y}(t)$	particle acceleration (m/s^2)
y(t)	particle distance (m)
g	gravitation constant = 9.81 m/s^2

However, in this setup, the net charges on the particles are neglected.

The simulation works have been confirmed by the measurement using an acoustic instrument. The height of the particle jump can be estimated from the time between two consecutive impacts during its excursion [5].

The comparison of different particles at 1 p.u. are shown in figure-5:

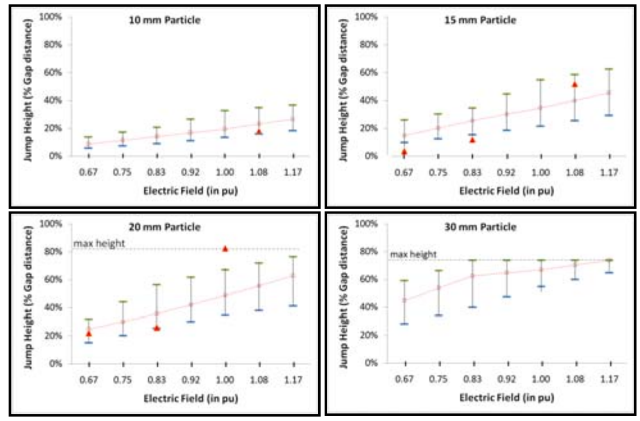

Figure 5. The maximum jump of different particles under AC voltage 1 p.u.

The simulation results are presented in figure 5 in ranges, since the jumping height from the calculation depends on the restitution coefficient factor (CR), which is a constant that represents the remaining impulse at the particle after its bounce at the bottom electrode.

The experimental results are indicated in figure 5 by the red triangles. Both results are comparable. An exception has been observed with the 30 mm particle. It was probably due to the microdischarge at the longer particles that limit the maximum jump.

Breakdown matrices have been determined by placing the particles at different distances in between the gap and being subjected to LI with maximum amplitude of 3.5 p.u. Instead of AC + LI, only LI has been applied since the time duration of the impulse is much shorter than the AC voltage. The matrices are given in figure 6:

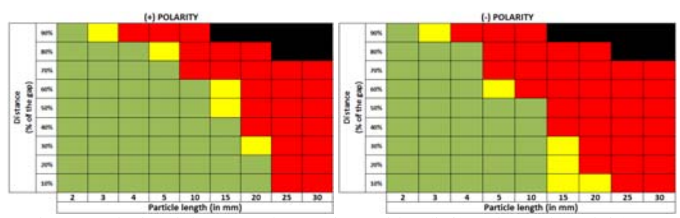

Figure 6. The breakdown matrices under positive (left) and negative (right) LI

In these matrices, the red colored columns represent the situation when the breakdown had been observed in the experiments, the green colored columns are the area without any breakdown, and the yellow colored columns are the unknown situations. The black columns are the area where the particle reached the inner conductor and became a protrusion.

The breakdown area has been distinguished by combining the breakdown matrices with the estimated maximum height from the simulation works. The results are shown in figure 7 below:

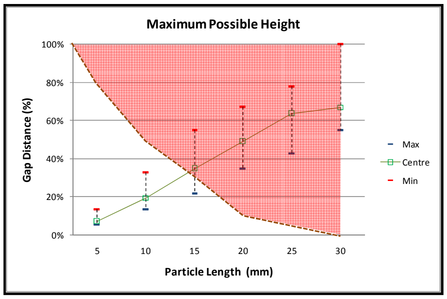

Figure 7. The breakdown area based on the experiments with LI and the simulation works under AC voltage.

According to this figure, the critical particle length under AC+LI overvoltage was 15 mm since these particles were able to jump into the critical distance where a breakdown might occur. It should be noted, the breakdown area shown in figure-7 represents the worst possible situation when LI is in phase with the maximum crest of AC voltage.

C. Investigation under AC + VFTO

The similar particle setup has been implemented during the investigation under AC + VFTO. The maximum VFTO of 2.1 p.u. has been generated and the breakdown occurred only from the experiment with the 30 mm particle at 90% of distance gap. The breakdown area then determined as shown in figure 8:

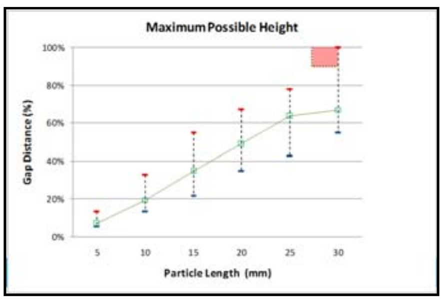

Figure 8. The breakdown area based on the experiments with VFTO and the simulation works under AC voltage

By using the similar approach as in the experiment with the AC + LI, the critical particle length under AC + VFTO was 30 mm.

VI. PARTICLES DETECTABILITY

The detectability of the particles during the GIS operation has been investigated. Three different detection methods have been performed by means of partial discharge measurements:

1. Acoustic method,
2. PC conventional method,
3. UH/VHF method

An example of the measurement results with the 15 mm particle under AC voltage 1 p.u. is given in figure 9.

Based on the experiments, all three methods were successfully detect the free particles with the minimum sizes of 2 - 5 mm.

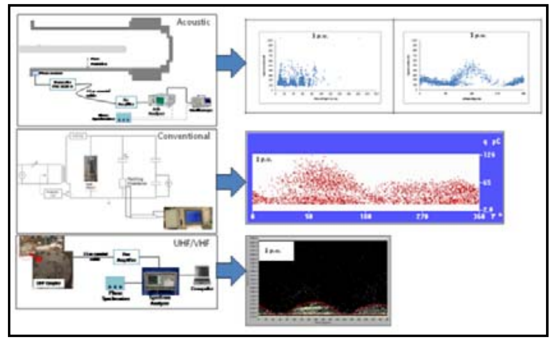

Figure 9. The patterns observed from three different partial discharge detection methods

VII. CONCLUSIONS

The particles with the lengths ranging between 2 mm to 30 mm had been subjected to different voltage stresses, namely: AC voltage, AC + LI overvoltage, and AC + VFTO. The critical particle lengths as well as their detectability are summarized in Table I.

TABLE I. PARTICLE CRITICAL LENGTH UNDER DIFFERENT (OVER) VOLTAGES WITH THEIR DETECTABILITIES

(Over)voltage Stress	Amplitude (in p.u.)	Critical Length	Detectability
AC	1	10 mm	Yes
AC+LI	3.5	15 mm	Yes
AC+VFTO	2.1	30 mm	Yes

As conclusions, the particles with the minimum length of 10 mm are dangerous to the insulation system, since they are able to trigger the breakdown under AC continuous operating voltage. Different measurement methods presented in this paper are able to detect these particles to avoid the failure.

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