Charge Accumulation in Polymers for SF_6-Free Hybrid Gas/Solid Insulation System

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***Abstract*— To replace SF_6 in electrical applications, it is essential to investigate charge accumulation in the solids used in hybrid insulation systems. This thesis develops a method based on surface potential decay (SPD) to characterize materials used in hybrid insulation systems and to predict their influence on gas discharge. In this work, experiments were carried out on PP, PVC, PVDF, and PTFE samples. Decay curves were analyzed to determine trap densities, and charge distribution maps (cartography) were used to obtain surface charge densities. Finally, COMSOL Multiphysics® simulations were used to predict streamer inception (streamer criteria). The study demonstrates that a bi-exponential mathematical model is an useful tool for analyzing trap densities, and that the combined experimental and simulation approach is an helpful tool for identifying and excluding unsuitable polymers for this application.**

I. Introduction

Sulfur hexafluoride is the most impactful greenhouse gas: 1 kg of SF_6 is equivalent to 23,5 tons of CO_2. Climate change is driving the replacement of SF_6 in high- and medium-voltage insulation. There are new eco-friendly options, especially for medium-voltage electrical equipment. The insulation in such systems is hybrid, consisting of pressurized air and a solid dielectric, typically a polymer. This study aims to assess the influence of solid dielectric properties on surface charge accumulation and thus on electric field reinforcement.

II. Methods

The physics of gas discharge has been studied: focus on streamers (pre-breakdown phenomena) with and without the solid insulator, based on literature review and experimental results from G2Elab. Subsequently, the work is structured into the following key steps:

A. SPD Experiment

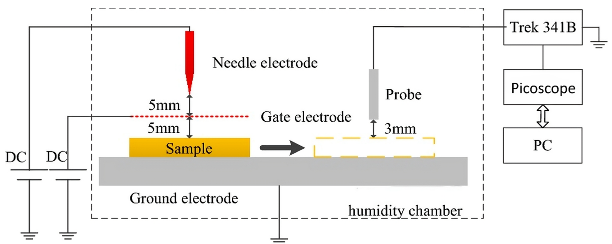

Figure 1: Set-Up Experiment.

Surface charges are deposited on the samples using the corona triode, and the surface potential is subsequently measured with a Kelvin probe (Figure 1). A double exponential function (1) is used to fit the surface potential decay curves, considering shallow and deep traps involved in the de-trapping process:

$$V_s(t) = A_{fast}\ \exp(-t/\tau_{fast}) + A_{slow}\ \exp(-t/\tau_{slow}) \quad (1)$$

B. Data Analysis: Trap Energy Distribution

Considering the surface potential V_s measured at a point over time t, the trap energy distribution is given by [1]:

$$N(E_t) = \frac{\epsilon_0 \epsilon_r t}{kTf_0(E_t)lLq}\frac{dV_s}{dt} \quad (2)$$

where T is the absolute temperature and q is the Coulomb quantity of electrons, and $f_0(E_t)$ is the rate of initial occupancy of the traps. The analysis of the $t \cdot dV/dt$ curves state the trap behavior in terms of density, depth, and charge release time [2]. The plot (Figure 2) shows the contribution of traps at different energy levels to charge release.

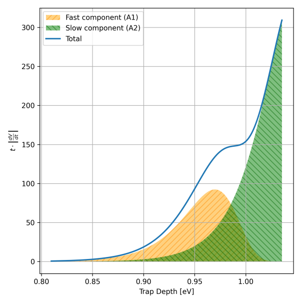

Figure 2: Trap Energy Distribution for a PVC sample. Mathematical model developed in Python.

C. Data Analysis: Surface Charge Density

From V_s over the whole surface (Cartography: Figure 3) the surface charge density is given by [3] :

$$\sigma_q = \epsilon_0 \epsilon_r V_s / d \quad (3)$$

Where d is the thickness of the sample. A Gaussian curve is derived and subsequently used in the simulation.

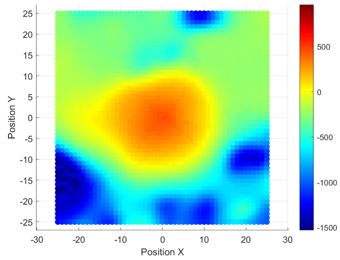

Figure 3: Cartography of PVC sample developed in MATLAB App Designer.

D. Simulation in COMSOL Multiphysics ®

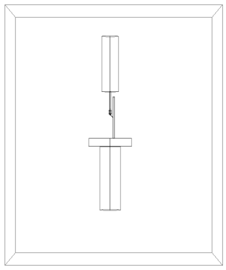

Figure 4: 3D Geometry: Triple Point.

The Electric Field is evaluated on the streamline and The value of the breakdown voltage is determined.

III. Results

Four different solids have been used: PTFE, PP, PVC, PVDF.

A. Conductivity Values

Fitting the experimental values of $V_s(t)$ with (1) and knowing that $\tau = \epsilon/\sigma$, the values in Table 1 have been found.

Table I: Calculated conductivity values σ (in S/m).

Material	σ_{fast}	σ_{slow}
PTFE	$1.52 \cdot 10^{-14}$	$5.81 \cdot 10^{-18}$
PP	$9.33 \cdot 10^{-14}$	$2.20 \cdot 10^{-17}$
PVC	$1.72 \cdot 10^{-14}$	$7.96 \cdot 10^{-16}$
PVDF	$1.32 \cdot 10^{-12}$	$5.78 \cdot 10^{-14}$

The conductivity values suggest the ability of insulating materials to retain electric charge over time.

B. Trap Energy Distribution

For the studied materials, it is observed that: PTFE and PP have few shallow traps and a large number of deep traps; PVC shows a strong initial release from shallow traps but also a gradual release, indicating a moderate number of deep traps; finally, PVDF exhibits a high density of shallow traps, resulting in a rapid discharge.
The curves were extended to a three-month time vector in order to predict the overall discharge times of the four materials. Among the examined samples, PVDF releases all its charge in less than an hour, whereas in PTFE the charge persists for more than three months.

C. Breakdown Voltage

The simulation of the Triple Point in COMSOL Multiphysics ®, considering the surface charge density (3) on the insulating solid, allowed the breakdown voltage of the system to be determined. The results are interesting because they show how charge accumulation in different materials either strengthens or weakens the electric field at the critical point, thereby influencing the discharge and, consequently, the breakdown voltage. Ultimately, among the studied materials, the triboelectric properties of PTFE contribute to the enhancement of the electric field, facilitating the discharge. The breakdown voltage has been found according to the streamer criteria.

Table II: Results of Streamer Criteria.

Sample Material	σ_q	V_{max} $[kV]$
PTFE	✗	4.70
PTFE	✓	2.68
PP	✗	4.70
PP	✓	5.87
PVC	✗	3.44
PVC	✓	3.73
PVDF	✗	2.13
PVDF	✓	2.20

IV. Conclusions

This work demonstrates that the bi-exponential model of surface potential decay over time is an extremely useful tool, as it allows the processing of large experimental datasets while minimizing the impact of noise introduced by the high data volume. Moreover, this approach enables the extension of analyses over very long time periods, providing an effective experimental tool to reduce measurement times without compromising accuracy. COMSOL simulations allowed a realistic assessment of how the accumulated surface charge affects the local electric field and, consequently, the breakdown voltage. Overall, the integrated experimental and simulation methodology enables the prediction of the suitability of polymeric materials for hybrid gas/solid insulation systems. The methodology applied to the studied materials highlighted that the least suitable for the reference application is PTFE, as its high triboelectricity leads to an increase in the local electric field and, consequently, a higher risk of streamer inception. Among the analyzed materials, PP appears to be the most promising, due to its higher breakdown voltage and its ability to retain charge over long periods.

References

[1] Y. Han, S. Li and D. Min, "Trap Energy Distribution in Polymeric Insulating Materials through Surface Potential Decay Method" *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 2, pp. 639, April 2018.

[2] P. Llovera and P. Molinié, "New Methodology for Surface Potential Decay Measurements: Application to Study Charge Injection Dynamics on Polypropylene Films" *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 11, no. 6, pp. 1049–1056, Dec. 2004.

[3] Laure Tremas, "Pre-breakdown and breakdown phenomena in air along insulating solids" *IEEE Transactions on Dielectrics and Electrical Insulation*, Electric power. Université Grenoble Alpes, 2017.