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Measurement of key dielectric properties for surface PD model under HVDC

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***Abstract*- The discharge over dielectric interfaces popularly known as surface discharge is a very common defect type that is associated with its respective discharge pattern under AC voltages. However, the same designs behave differently under DC voltages leading up to erratic PD behavior. To understand the process of surface discharge an equivalent circuit model is developed, and its influencing material parameters such as the volumetric and surface electrical conductivities and the relative permittivity are measured experimentally. This paper describes the methodology and setup of the measurement based on international standards. The final goal is to provide the constituent model parameters that can describe the surface discharge model under DC stress.**

I. INTRODUCTION

The design process of high voltage DC applications is a highly challenging task. The prediction of the electric field distribution under DC is dependent on several parameters such as the insulation temperature and the electrical conductivity [1]. In addition, when multiple dielectric media are involved such as, at interfaces, knowledge of more complex physical phenomenon such as space and surface charge formation is required. A solid awareness on fault characteristics and fault tolerance is a prerequisite for the design of robust applications [2]. Several investigations so far have focused on field grading materials (FGM) and other coatings that could make the fault tolerance of the DC design more predictable and controllable [3][4]. However, not much is known on the relationship between the material properties and its surface discharge characteristics. The PD behavior on solid dielectric surfaces though highly recognizable under AC, is very erratic in nature under DC. Therefore, as a first step, this paper would like to investigate the volumetric and surface electrical parameters of insulation materials. This will help not just in building the surface PD model but will also aid in defining the PD test conditions such as waiting time to DC steady state. For instance, the model parameters can be implemented in finite element simulations to estimate the time to steady state.

This contribution begins by describing the surface discharge model in terms of its circuit elements in section II. In the following sections III and IV, the AC and DC measurement of dielectric properties of the solid insulating materials are presented. The measurements are carried out in compliance with the associated IEC standards[6][7].

II. DISCHARGE MODEL

Consider a surface discharge model as shown in Fig.1 with a dielectric sample sandwiched between two electrodes. The creepage distance is represented by ‘r’ and will increase with increasing voltage. In order to deduce the equivalent circuit of this model, let us consider a coaxial arrangement with the high voltage (HV) electrode in the center and surrounded by the ground electrode. There exist two parallel paths to the partial discharge, one through the dielectric sample and the other over the dielectric surface. Based on the 3-capacitive model [5], the AC equivalent circuit can be drawn as shown in Fig.2a. Where one parallel capacitor represents the dielectric capacitance of the volume (C_{vol}) and the other parallel capacitance the surface/interface between the dielectric and surrounding air (C_s). As shown in Fig.1, since only a part of the dielectric surface (region with radius r) breaks down during partial discharge, the surface capacitance C_s is split into two parts, a healthy part represented by C_s and a part which breaks down represented by $C_{s,bd}$. In case of DC voltage stress, the capacitances only play a role in the transient state before the voltage reaches steady state. Therefore, the circuit representation for the DC transient stage is modified as shown in Fig.2b, with parallel resistors. In the pure DC steady state thereafter, the capacitances act as open-circuit and hence the circuit is further modified as shown in Fig.2c. The illustration of Fig.1 with coaxial arrangement is now reduced to the equivalent representation of Fig.2c.

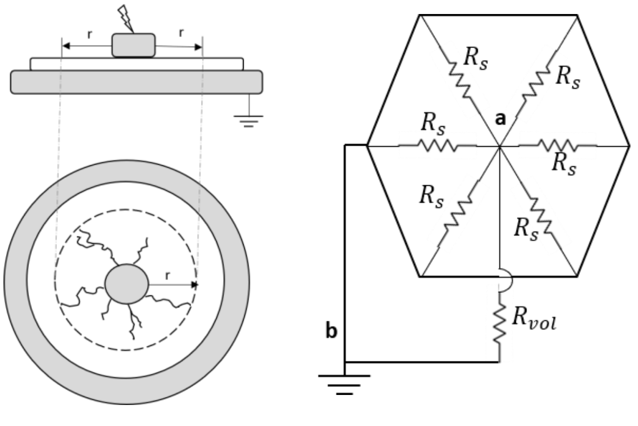
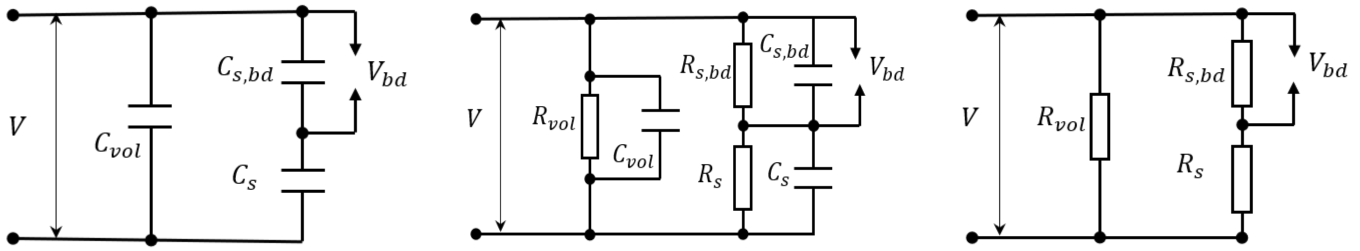


Fig.1. An illustration of the surface discharge process and an impression of the influencing circuit components under DC where terminal ‘a’ is HV and terminal ‘b’ is ground.



(a) AC (b) DC: $t < \tau$ (c) DC: $t > \tau$

Fig.2. The equivalent circuit of the surface discharge model for (a) AC, (b) transient stage of DC and (c) steady state DC.

In order to develop a surface discharge model for DC field conditions, the parameters on Fig.2 namely the volume and surface resistance and the relative permittivity/ dielectric constant of the sample (to derive the capacitance) must be known. The forthcoming sections describe the method of measurement of the above-mentioned quantities.

III. AC MEASUREMENTS

The dielectric constants of the insulating samples are measured using the Tettex 2830 dielectric analyzer together with the Tettex 2914 test cell for solid insulants. The devices used are shown in Fig.3. All measurements are made in ambient air at atmospheric pressure. The samples are cleaned prior to testing with alcohol and dried with cellulose-free paper. The dielectric samples are placed between the test electrodes and a uniform pressure of 2 N/cm^2 is applied to ensure good contact. The measurement of volumetric dielectric properties is done according to the standard IEC 62631-3-1 [6]. The measurement principle is based on a 3-electrode system consisting of namely 1: main (HV) electrode, 2: measuring electrode and 3: guard electrode as shown in Fig.4. The presence of the guard electrode helps to restrict/control the fringe fields that occur at the edge of the sample. The range and accuracy of the measuring system is as specified in Table.1.

Fig.3. Left: The Tettex 2830 dielectric analyzer and right: Tettex 2914 test cell for solid insulants.

The relative permittivity (ε_r) is measured directly based on eq.1.

$$C = \frac{\varepsilon_r \varepsilon_o A}{h} = C_o \varepsilon_r \qquad (1)$$

Where ε_o is the permittivity in free space and C is the measured capacitance of the sample, A is the effective surface area of the measuring electrode and h is the thickness of the sample.

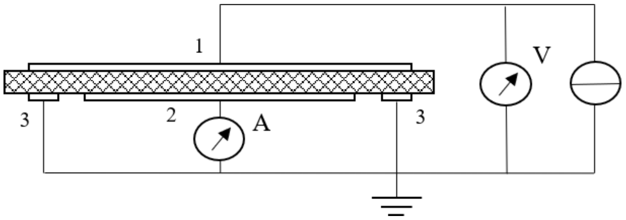


Fig.4. The circuit schematic for measurement of volumetric dielectric properties based on IEC 62631-3-1 [6].

Table.1. Technical specifications of the measuring system

Measured quantity	Range	Max. resolution	Accuracy
Dissipation factor (tan δ)	0… 100	1 x 10^{-6}	± 0.5 % rdg ± 1 x 10^{-5}
Capacitance	≥ 10 pF	0.001 pF	-
Relative permittivity (ε_r)	1… 30	1 x 10^{-3}	-
Resistivity (solids)	2.4 MΩm - 80 TΩm	-	-
AC test voltage	5… 2500 V	1 V	± 0.3 % rdg ± 1 V
DC Test voltage	250-2500 V	25 V	+10 % rdg +20V

IV. DC MEASUREMENTS

The DC tests are carried out to measure the volume and surface resistivities of the dielectric samples. The volume conductivity is measured using the setup shown in Fig.4, with the 3-electrode setup, using the annular ring electrode as guard electrode. The volume resistivity (ρ_v) of the sample is derived from the value of measured resistance (Rs) using the relation shown in eq.2.

$$\rho_v = \frac{R_s A}{h} \qquad (2)$$

Where A is the effective surface area of the measuring electrode and h is the thickness of the sample. It becomes highly challenging to measure the resistivities of samples with high resistivity (or thick samples >3 mm). In case such cases, using thin samples (0.1-1 mm) helps improve the measurement sensitivity. The results can be influenced by many factors, including test conditions like temperature and relative humidity. Applied voltage, polarization time, material and geometry of electrodes are other factors that can influence the measurement greatly. The IEC standard defines a waiting time of 1 min for the measurement of volume resistance. However, for samples with a long polarization time, the waiting time can be increased accordingly in order to record the complete curve of resistance/ polarization current vs. time. This will also provide insight into the surface discharge behavior of the sample during a PD test.

The surface resistance values of dielectric samples are measured using a similar 3-electrode setup as for measurement of volume properties, however, with the reversal of the HV and guard electrodes as shown by the circuit schematic in Fig.5. The current flowing in the annular ring is measured and the surface resistivity (ρ_s) is deduced using the expression given by eq.3.

$$\rho_s = \frac{d_2+d_1}{d_2-d_1}.\pi.R_s \tag{3}$$

Where R_s is the measured resistance, d_1 is the diameter if the inner electrode and d_2 is the inner diameter of the ring electrode.

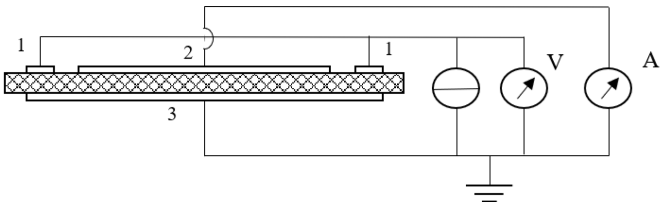


Fig.5. The circuit schematic for the measurement of surface dielectric properties based on IEC 62631-3-2 [7].

V. RESULTS

The results of measurement of dielectric constant (ε_r), volume and surface resistivity are summarized in Table.2. Samples 1 and 2 are dielectrics for power cable application, sample 3 is a high-grade Teflon sample used commonly in HV constructions. The last sample, 4 is a rubber-based dielectric possibly loaded with carbon black (shown from its black color), this can be noted based on the poor resistivity values and high dielectric constant of 4.81.

With respect to polarization time, samples 1 and 3 have a very short polarization time lasting less than 1 min. Sample 2 has a slow changing polarization current over 30 min long. While sample 4 has a polarization current over the first 10 min. The recording of the dropping polarization current/ increasing resistance over time for sample 4 is shown in Fig.6. Similar plots are obtained for all samples.

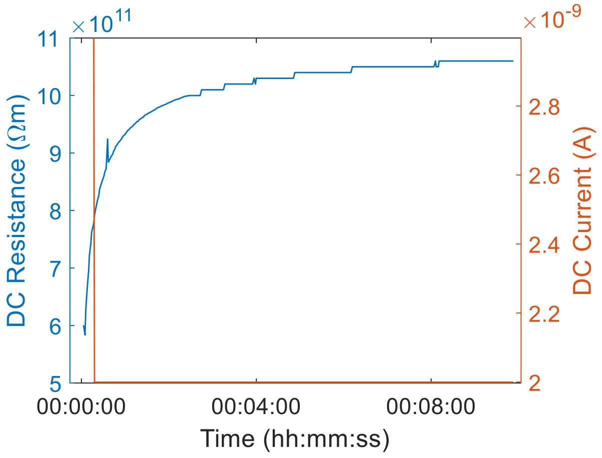


Fig.6. Plot of measured DC resistance and polarization current for sample 4.

A. *Challenges*

The resistivity measurement of high resistive samples (~100 TΩ) is a challenging task since the current measured is in the range of nA or pA. A fluctuation of a few pA due to external disturbance can result in a fluctuation/error on the output of over 100%. Therefore, using a closed measurement setup with the Tettex 2914 is a safe and reliable method.

Some of the dielectric samples used in the experiment had a resistance value beyond the range of the Tettex 2830. In these special cases, it was required to use a special PetaOhm meter from Tettex, type 5476. This extended the measuring range 60 folds compared to the Tettex 2830.

Surface resistance measurements were performed using a specially built electrode arrangement of dimensions different from that used for volume resistivity measurements. This was because the gap distance in the electrode arrangement of Fig.4 was 0.5 mm and the electrode thickness was over 10 mm. This air gap created a high measurement uncertainty and also limited the maximum applied voltage while used in the arrangement shown in Fig.5. Therefore, the sizes recommended by IEC 62631 with a gap distance of 5 mm, fitted with a specially designed Teflon ring was manufactured for the purpose. An image of the special electrode arrangement is shown in Fig.7. In the future, the impact of the Teflon ring on the measured values of resistance can be studied. The values of surface resistivity of samples 1 and 3 are the same

Table.2. Results of the measurements of dielectric properties.

Sample identifier	Thickness (h) [mm]	Dielectric constant (ε_r)	Volume resistivity (ρ_v) [Ω]	Surface resistivity (ρ_s) [Ω]
Sample 1	0.58	2.18	$2.98e15$	$6.91e16$ (max)
Sample 2	2	1.57	$2.4e13$	$1.04e16$
Sample 3	0.6	1.95	$6.4e15$	6.91e16 (max)
Sample 4	2	4.81	$9.62e11$	6.91e15

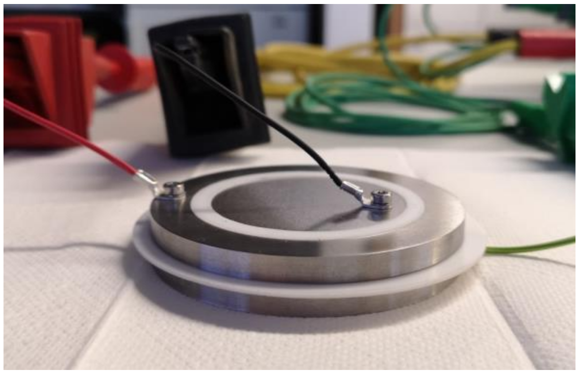


Fig.7. Electrode arrangement with a Teflon ring installed in the gap, used for surface resistivity measurements.

since the measurement instrument has reached its maximum measuring range.

A review paper on the old IEC standard for measurement of volume and surface resistivities of insulating materials, IEC 60093 [8] provides a deep understanding on the challenges of such measurements and also estimates the error for several possible scenarios.

VI. CONCLUSION

This contribution highlights the procedure used for the measurement of dielectric properties relevant towards the study and analysis of surface discharge process under DC voltage conditions. The estimation of these dielectric properties opens the possibilities of developing a simulation model to understand the charge transfer process at the dielectric interface.

Developing a good simulation model followed by recursive partial discharge testing of multiple samples over a wide range of resistances (various dielectrics) in order to obtain the discharge pulse stream which represents the defect progression/process and correlating them with the results of the dielectric properties can provide answers to the nature of DC surface PD. The polarization time of the sample is also an important marker when it comes to DC design since it provides information on the charging time or time to steady state (DC field) of the particular design. By recording the polarization and depolarization curve it is also possible to determine the charge holding capacity of the insulting material. Therefore, this paper would like to stress on the crucial role that the dielectric material properties can play in the DC design of power components.

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