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AN EXPERIMENTAL ESTIMATION OF THE AVERAGE MOBILITY CHANGE OF FREE ELECTRONS DURING DIELECTRIC AGING AT THE MODEL SOLID – LIQUID INSULATORS

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ABSTRACT
In this paper, an experimental estimation of the average mobility change of free electronic carriers at the model solid-liquid insulators during their dielectric aging. For this purpose specimens of industrial bakelite were electrically stressed by an imposed high AC voltage. The electrode set-up used was metal tip-sample of solid insulator-metal in an environment of transformer oil. Measurements were taken by increasing the imposed voltage in steps of 1 kV until the ultimate breakdown of the insulators. The values of the average mobility of the model was calculated through the measurement of charge which flows through the sample, as a result of partial discharges, the kinetic energy of free electrical carriers and the applied field value. From these measurements the exponential increase of the average mobility change of the model solid-liquid insulator in relation with the value of the imposed electric field was noted. In satisfactory agreement with the theoretical data it seems that the average mobility is increased due to the impact ionization which takes place during the dielectric aging stages of the insulating model.

KEY WORDS
Electrical Insulation, Partial Discharges, High-Voltage Measurements, Solid Polymeric Insulators, Electrical Protection.

1. Introduction

Following extensive research, it can be said that the appearrance of aging and penetration of solid insulators during their electrical strain under high voltage are explained with methods which can be classified into two theories [1, 2]:

i. Macroscopic theory and
ii. Quantum Mechanical theory.

According to the macroscopic theory, we can perceive four theoretical forms of penetration (breakdown) depending on the factors, which play a key part in its realization. These penetration forms are: thermal penetration, electrical penetration, electrochemical penetration (or aging) and, thermo-chemical penetration [1-3]. In the majority of cases, breakdown may be the result of some or all of the above factors. The quantum mechanical theory principally concerns the energy of free electrical carriers (electrons), which are produced during the aging of the material. The lack of homogeneity within the solid insulator induces the appearance of disturbance bands between conductivity and strength bands, which, like intermediate energy levels, facilitate the transmission of electrons to the conductivity band [1, 2].

A determining factor for the creation of free electrical carriers is the value of the imposed field [2]. Above a threshold value of the electric field the electrons obtain an increased kinetic energy, which they emit as electromagnetic radiation - whose spectrum during aging ranges from acoustic waves to ultra-violet radiation - during their absorption at the anode electrode [1, 2]. The spectrum of the above radiation during penetration is able to extend to values, which are considerably higher than 20 eV. The above theory is referred to in the bibliography as impact ionization [1, 2]. Impact ionization is related to the appearance of differential resistance to the material, the reason why the accumulation of the electric carriers from the electrodes takes place in groups. The spectrum of the emitted electromagnetic radiation depends on the surplus energy of the free electrical carriers during their constrained deceleration by the electrodes [2].

A factor, which forms a criterion for the evaluation of insulators, is the mobility of the free electrons (b). This factor gives us information about the energy losses in the insulators, which in the case of the imposition of AC high voltage may be due to:

i. The energy consumption during the continuous alternation of the electrical trend of the bipolar at the rate of the polarity alternation of the AC voltage.
ii. The very minimal specific electrical conductivity present in insulating materials.

An increase of the mobility of the free electrons leads to an increase in the insulator conductivity and consequently to a reduction of its dielectric strength [1].

The transfer of the flow charge q through the insulating material samples during the application of high voltage is easily determined by the use of the potential build up across a capacitor C_m, as follows [1, 2, 4]:

$$q = C_m u_m, \quad (1)$$

where, u_m is the instantaneous value of the potential profile across the measuring capacitor C_m.

Therefore, the total electric charge increase of partial discharges (ΔQ_m), is calculated using the expression 1:

$$\Delta Q_m = C_m \Delta U_m, \quad (2)$$

where, ΔU_m is the total width of the observed potential steps across u_m due to the presence of partial discharges [1, 2, 4, 5].

The partial discharges (P. Ds) at the samples were initiated when the value U of applied high voltage reached a certain threshold value (U_o). In this case, a single potential step at the potential profile across the measuring capacitor C_m, is observed, signifying the initiation of partial discharges. This value of the applied voltage was defined as "Threshold Voltage of Partial Discharge Initiation". Specifically U_o is the root mean square value (r.m.s. value) of the specimen's applied high AC voltage. The corresponding total electric charge of partial discharges at threshold value of the applied voltage U_o was defined in literature as "Total Electric Charge of Partial Discharges Initiation" (ΔQ_o) [2, 4]. According to the expression 2, the total electric charge of partial discharges initiation (ΔQ_o) which corresponds to threshold value of the applied voltage U_o, is calculated by the relation 3 [1, 2, 4]:

$$\Delta Q_o = C_m \Delta U_o, \quad (3)$$

where, ΔU_o is the total width of the observed potential steps across u_m due to the presence of partial discharges initiation at voltage level U_o.

In this work, samples of solid insulators were electrically stressed by the application of high AC voltage through a "tip-plane" set-up in an insulating oil environment. Measurements were calculated of the electric charge, which flows through the samples due to the partial discharges and the emitted electromagnetic radiation due to the absorption of kinetic energy of electrons in anode electrode [1]. Following this, the average mobility change of the sample model (metal tip - solid polymeric dielectric - metal plane combination) in an transformer oil environment, was calculated in order to determine the relation between the average mobility variation and the imposed electric field. The solid insulator "industrial bakelite" was used for the measurements. The insulating oil was the typical transformer oil. The environmental temperature was 20 °C (laboratory temperature).

2. The Experimental Arrangement and Measuring Procedure

In Fig. 1, a simplified schematic diagram of the measuring circuit is given. This included a high-voltage transformer, a voltage divider, a shielded control room and the sample setup.

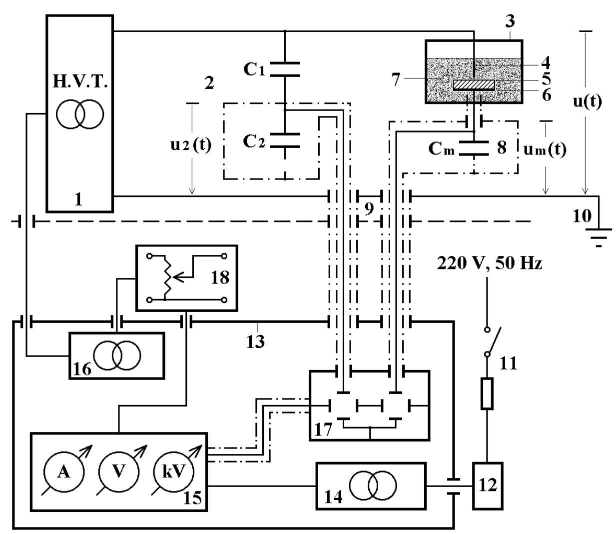

Figure 1.
Simplified schematic diagram of measuring circuit.
1: High voltage transformer (220 V/100 kV, 5 kVA), **2:** Voltage divider (C_1 = 1200 pF, C_2 = 4 μF) and measuring network of applied AC voltage, **3:** Sample container (made of diaphanous PVC), **4:** Tip-electrode (the tip radius is 0.3 mm), **5:** Polymeric solid insulator sample, **6:** Plane-electrode (the plane diameter is 150 mm), **7:** Surrounding insulating oil (transformer oil), **8:** Partial discharges measuring capacitor C_m (20 nF), **9:** Coaxial measuring cables, **10:** Electrical earth, **11:** Voltage supply, **12:** L.P. filter, **13:** Shielded room, **14:** Isolating transformer, **15:** Control panel, **16:** Isolating transformer, **17:** Dual beam oscilloscope, **18:** Variac (220 V, 5 kVA)

The characteristic operational magnitudes of high voltage transformer were 220 V/100 kV, 5 kVA. The voltage divider (C_1, C_2) and the measuring network of applied alternating high-voltage that was used includes a high voltage capacitor C_1=1200 pF and a series conduct measuring capacitor C_2=4 μF. The resulting partial discharges at the samples were detected in the form of certain potential steps at the voltage profile ΔUm across the measuring capacitor C_m. For these measurements, the capacitance of the C_m was chosen to be 20 nF.

The operation was controlled and the oscillograms were taken from a shielded room, which attenuated at least 50 dB for signals up to 1 GHz. The network also included a voltage stabilizer (3 kVA), which provided a constant voltage of 220 ± 1 V_{AC} even for a fluctuation of the supply voltage up to 10%. Harmonics, which might be added by the stabilizer, were less than 0.8%. Outside the shielded room, there was a high-frequency reject filter, and inside an isolating transformer (220 / 220 V, 5 kVA), for noise free mains supply. The attenuation of the above filter was 100 dB over the significant frequency range. The control panel for measurements included a variac (0-220 V, 5 kVA), which supplied the H.V. transformer. Other auxiliary circuits for protection and control, the synchronizing device, volt and current meters were the standard equipment of a control panel.

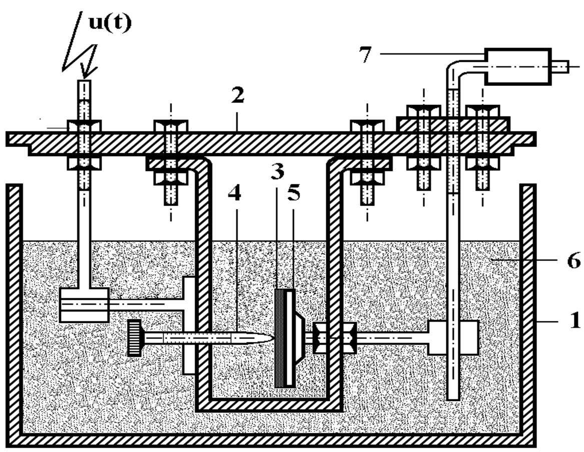

Figure 2.
Sample container with the assembly of electrodes and sample. The sample is in physical contact with the electrodes and the whole assembly is immersed in insulating oil (transformer oil).
1: Sample container (manufactured by diaphanous PVC), **2:** Container cover, **3:** Polymeric solid insulator sample, **4:** Tip-electrode (the radius is 0.3 mm), **5:** Plane-electrode (the diameter is 150 mm), **6:** Surrounding insulating oil, **7:** Partial discharges measuring capacitor C_m (20 nF).

The high voltage transformer was supplied through a variac with the line voltage (220 V, 50 Hz). The measuring capacitor (C_m=20 nF) was connected in series with the sample to the electrical earth, using the so-called "straight partial discharges test circuit", and was used to detect partial discharges at solid insulating material [6]. Discrete potential steps appearing on the voltage profile across C_m, were monitored on a dual-beam oscilloscope and provided the information required to investigate partial discharges and estimate the total voltage increase.

Fig. 2 shows the sample container (1, 2), which housed the test object arrangement with a tip-plane electrode assembly. The solid dielectric specimen (3) was in physical contact with the hyperbolic tip electrode (4) and the plane electrode (5). The tip-electrode radius was 0.3 mm and the plane-electrode diameter was 150 mm. The samples were cut in wafers of 150 mm diameter and their thickness was 1 mm. The sample and the contacted electrodes were immersed in insulating oil (type JS-A, manufactured according to B.S. 148 of 1959) (6) in order to increase the dielectric constant of the surroundings and to avoid undesirable spark formation. The measuring capacitor C_m (7) was connected in series with the sample.

The first measurements were taken as soon as the first partial discharges were detected at the threshold voltage for partial discharges initiation (U_0). Then, the measuring procedure continued, with the applied voltage gradually increased in steps of 1 kV at a time. At each voltage level, the electrical stress duration was 10 minutes.

A great number of oscillographs for the measurement of voltage drop $u_m(t)$ across the measuring capacitor C_m provided the possibility to elaborate the measured magnitudes.

3. Discussion and Measurements Results

The corresponding values for the electric field at the tip-plane electrodes are evaluated using hyperbolic tip analysis [7]. According to this, the value of the electric field E is given by:

$$E = 2 \cdot U / [r \cdot \ln(4\, d / r)], \quad (4)$$

where, r is the tip radius (r = 0.3 mm), d is the separation between the electrodes or the specimen's thickness (d=1 mm), and U is the root mean square value (r.m.s. value) of the specimen's applied high AC voltage (50 Hz).

The average velocity value (v) of the free electrons in dielectric due to the appearance of partial discharges is given by the relation [1, 8, 9, 10]:

$$v = [2\, \Delta W / m_e]^{1/2}, \quad (5)$$

where, m_e is the rest mass of electron (m_e = 9.109558 10^{-31} kg) and ΔW is the average value of the kinetic energy of the free electrons or the average value of the emitted electromagnetic radiation after the collision of the electrons on the anode electrode. According to the literature, when C_m = 20 nF, ΔW is approached by the relation [1, 4]:

$$\Delta W\ [eV] = 0.5\ \Delta U_m\ [V], \qquad (6)$$

The average mobility value of free electrons (b) is given by the relation [1, 8, 9]:

$$b = v / E = \sigma / (N\ q_e) = \sigma / \Delta Q_m, \qquad (7)$$

where E is the field value applied on the material, σ is the specific electrical conductivity per volume unit (1 m^3) of the dielectric [1, 8, 9], N is the number of the free electrons, q_e is the electrical charge of an electron (q_e = -1.60217 10^{-19} C) and ΔQ_m is the total charge of free electrons due to the appearance of partial discharges.

From the relations 4, 5, 6 and 7, a numerical expression of the average mobility value of free electrons (b) arises (when C_m = 20 nF):

$$b = v / E = \sigma / (N\ q_e) \rightarrow b = [2\ \Delta W / m_e]^{1/2} / E, \qquad (8)$$

Therefore, the relation 8 takes the following final numerical form for a model of the type tip-plane electrodes setup:

$$b = [2\ \Delta W / m_e]^{1/2} / E \rightarrow$$
$$\rightarrow b = [2\ \Delta W / m_e]^{1/2} / \{2 \cdot U / [r \cdot \ln(4\ d / r)]\} \rightarrow$$
$$\rightarrow b = 0.707\ [\Delta W^{1/2}\ r \cdot \ln(4\ d / r)] / [U\ m_e^{1/2}], \qquad (9)$$

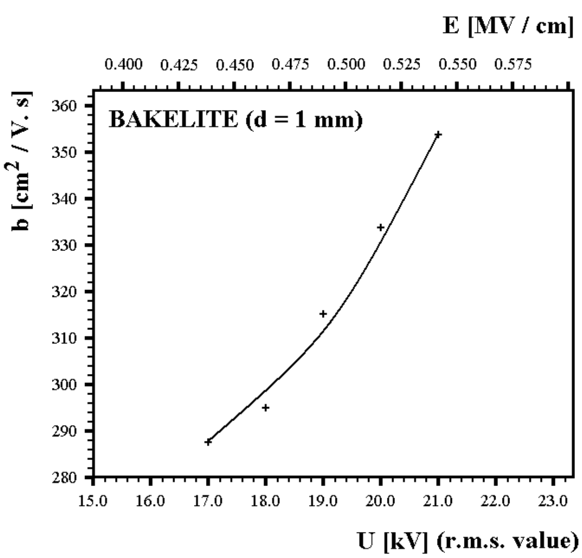

Figure 4.
Experimental curve of the calculation results b = f(U, E) in relation with the root mean square value of the applied high AC voltage (U) at the samples and the corresponding electric field (E).
Solid Insulating Material: Industrial Bakelite immersed in insulating oil, **Samples Thickness:** 1 mm, **Electrical stress duration:** 10 minutes at each applied voltage level (1 kV).

For the case of the stress time duration of 10 minutes per applied voltage level 1 kV the experimental results and the calculation of the of the average mobility value of free electrons (b) versus the root mean square value of the applied high AC voltage U or the corresponding electric field E at value U (according to the equation 9) are shown in Fig. 4. These results correspond to measurements of industrial bakelite samples, with a diameter Φ = 150 mm and a thickness d = 1 mm (the volume V of samples was $V = d\ \pi\ \Phi^2 / 4$) immersed in insulating oil at Partial Discharges Initiation and samples Breakdown. The corresponding products b = f(U, E) of various insulating materials (e.g. Pertinax-phenol impregnated pressboard, Glimmer, Porcelain, Transformer Oil, Glass, Presspan, etc) are almost analogous [1].

The experimentally determined values of the products in the case of a 1 mm thick industrial bakelite sample immersed in insulating oil are given in TABLE 1. These results correspond to the values, which resulted from measurements on 10 pieces of specimens from both of the above material stressed, at each voltage level These values are in a good agreement with the other corresponding system results [1]. In satisfactory agreement with the theoretical data it seems that the average mobility is increased due to the impact ionization which takes place during the dielectric aging stages of the insulating model [1, 2].

TABLE 1
Total values of the products (b) received from measurements results of Fig. 4.

	Samples P. Ds Initiation	**Samples Breakdown**
Applied Voltage Stress U [kV]	17.00	21.00
Applied Electric Field E [MV/cm]	0.4375	0.5405
Average value of the Electrons Energy ΔW [eV]	4.5	10.4
Average mobility value of free electrons (b) [cm^2 / V s]	287.5	353. 8

4. Conclusion

During the dielectric aging of solid insulator industrial bakelite with the application of high AC voltage through the electric field of tip-plane electrode assembly in a transformer oil environment partial discharges are produced. Following a threshold value of imposed electric field the partial discharges appear subsequently as potential steps of the capacitor C_m voltage. During each potential step an electric charge ΔQ_m is produced which flows through the insulator. According to the quantum mechanical theory, fast moving electrons of dielectric convey their energy in the form of electromagnetic energy during their collision with the anode electrode.

The experimental results show that the average mobility value of free electrons change has an exponential increase in relation with the imposed electric field and this may come as an indication of the impact ionization effect. The actual value of the average mobility value of free electrons (b) for the combination of the industrial bakelite samples 1 mm of thickness in an insulating oil environment during its stress from AC high voltages is from 287.5 cm^2 / V s to 353.8 cm^2 / V s.

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