

Corona Charging and Charge Decay on Polyethylene Terephthalate Films (PET)

Karima Smili¹, Lazhar Herous²

¹Laboratory of Electromechanical Engineering, Higher School of Industrial Technologies, Cité Safsaf , BP 12, Sidi Amar Annaba 23220, Algeria

²Laboratory of Electrical Engineering, University of Badji Mokhtar, BP 401, Guelma, 24000, Algeria

Abstract

Surface potential decay (SPD) measurements have been considered as the most appropriate technique to investigate the electrical properties of insulating materials. Its main interest is to avoid any contact with the surface; providing that charge is deposited by means of a DC corona discharge. Besides, the interpretation of the surface potential evolution remains a major problem. For this reason, this study aims at considering surface potential measurements and the mechanisms of the potential decay and transport processes that might be involved in the decay. To reach a conclusion, samples that were used took the form of polyethylene terephthalate films (thickness: 0.5 mm; surface: 50 mm x50 mm). A negative corona discharge produced in a needle-grid-plate electrode system was employed to charge the surface of the film samples. All surface potential decay measurements were carried out in a commercial climatic chamber, where relative humidity RH and temperature T were rigorously controlled. Initially, we have shown an injection process of the charge deposited on the surface of the material. The investigation on the kinetics of charge carriers (charge carrier mobility), allowed us to determine the mobility of the charge derived in the material. We noted a strong dependence of the charge density put on the evolution of SPD.

Keywords: Charge injection, corona discharge, mobility, polymer, surface potential decay.

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1. Introduction

The measurement of the isothermal surface potential decay after charge deposition provides an appropriate method to study the electrical properties of insulating materials. Its main advantage is the avoidance of any contact with the surface and potential measured by a vibrating reed probe.

Since several years, synthetic polymers have been applied in electrical industry due to their excellent electrical, thermal, and mechanical properties [1], [2], [3].

In addition to their function of insulating, these materials store electrical charges. An important finding made about these materials and their degradation is closely related to the ability of the equipment to store electrical charges. One of the emerging data of research in recent years is the importance of the charges stored in the insulator on the dielectric withstand, whether volume breakdown observed when the electric field is directed according to the thickness of the insulation, or surface breakdown when collinear with an insulating-vacuum, insulating-gas interface [4], [5].

These have a detrimental effect on the dielectric properties of the materials. The charges modify the

spatial distribution of the electric field and increase the internal energy of the dielectric by introducing a term of electrostatic energy. They modify their properties locally and cause premature aging [6], [7].

In fact, the accumulation of charges on the surface or in volume of the polymers under electrical stress is at the origin of the localized strengthening of the electric field leading to the appearance of partial discharges followed by breakdown of the dielectric. Depending on whether the conductive path develops in volume or surface, voluminal or surface breakdowns can be discerned. In addition to the field of high voltage, the problem of the leakage of charges can arise in the case where it is necessary to guarantee the antistatic behaviour of the material. It can also be present in different forms of electro-reprography by copying on the surface of the dielectric and probably occurs in micro-electric circuits too.

Meanwhile, solid insulating polymers are used in hostile environments where they may be subjected to water attack, high static non-ionizing radiation and other corrosive materials or reactions. Therefore, the insulation properties are deteriorated and involve a premature ageing of electrical insulation.

Electrostatic charges can play an undesired role in diverse industrial applications, particularly, in plastic industry and in high impedance circuitry.

The main fields of industry source of numerous works on surface potential decay are: Electro-optics (photocopies and laser printers) [8], electrets materials [9] and electrical industry working on insulating polymer developments for high voltage insulation [10], [11].

If these charges are injected into the volume of material either by strengthening the local electric field, or by interaction with the material, they will induce local heating and degradation of physico-chemical properties. The latter will impair the insulating properties of the material and thus lead to the breakdown of the dielectric.

To understand the origin of electrostatic nuisance and optimize the performance of polymers, it is important to have appropriate knowledge on generation and charge transport processes. In this respect, a great effort has been devoted to the characterization and understanding of charges transport in insulation polymer [10], [11], [12], [13], [14], [15].

Despite recent progress achieved with measuring instruments, identifying the predominant mechanism remained obscure. The process of conduction, polarization or charge injection, trapping process /de-trapping is complex phenomena and difficult to explain.

One of the experimental techniques used to investigate the charge carrier transport in solid

insulating polymers is the surface potential decay method. Its main interest is to avoid any contact with the surface; providing that the charge is deposited by means of a DC corona discharge and that potential is measured by a vibrating reed probe, or by an induction probe. Many experimental works have been carried out with this powerful method [10], [13], [14], [16], [17].

The great diversity of parameters influencing these mechanisms makes the study and the interpretation of the processes difficult. Several physical processes namely, surface conduction, polarization phenomena, charge injection, and atmospheric neutralization, can be responsible for the potential decay after corona charge deposit. The possible effects of piezoelectric phenomena under the influence of electrostatic pressure at high field, could be also added.

The recent literature on potential decay measurements is dominated by the hypothesis of injection and polarization phenomenon of the charge deposited on the surface. The “Cross-over” of the curves which were reported initially by Leda and co-Workers [16] on polyethylene and, also, has been observed by other research works [10], [14], [18] has been widely admitted as an experimental evidence of a partial injection into the bulk of the charge deposited on the surface.

2. The Experimental Techniques

The surface potential decay experiment is described in Figure 1.

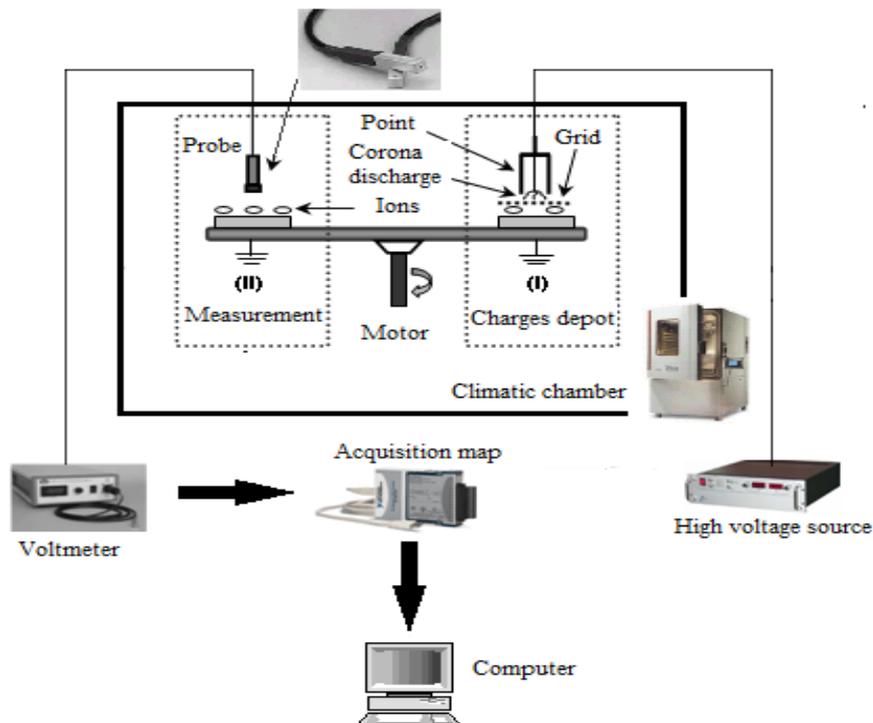


Figure 1. Experimental setup for the study of the surface potential decay of PET samples

The samples were charged on their free surface by exposure to a corona discharge generated by a needle electrode situated above the grounded metallic plate and connected to a negative DC high-voltage supply V_p .

A grid electrode, connected at a different negative DC potential V_g , was interposed between the needle electrode and the grounded plate. In this way, a reasonably uniform field could be generated in the gap between the grid and the surface of the PET samples. By selecting appropriate corona point and grid potential, V_p and V_g respectively, it was possible to charge the polymer surface with ions of either sign.

The surface potential was limited by the grid potential V_g . After charging, the grounded metal plate was rotated, so that to transfer the sample under the probe of an electrostatic voltmeter (Monroe Electronics), connected to the computer that controlled the measuring procedure. The surface potential was thus continuously measured and recorded. All surface potential decay measurements were carried out in a commercial climatic chamber, where relative humidity (RH) and temperature (T) were rigorously controlled. The duration of sample exposure to the corona discharge was 1s prior to corona exposure, the samples were maintained for one hour in the conditions prescribed for each experiment.

3. The Experimental Details

Measuring the surface potential involves the use of a measuring probe that operates according to the vibrating capacitor principle [19].

The vibration of a small flap inside the probe varies the capacity between this flap and the surface. In the case where there is a potential difference V across this capacitor, a current proportional to the value of the electric potential will flow in the circuit according to:

$$I(t) = \Delta V \times \frac{dC}{dt} \quad (1)$$

The principle of measurement is to permanently cancel this current by varying the potential of the probe and the shutter, the probe is therefore at the same potential as the surface, which allows to disturb the sample as little as possible. It is then sufficient to measure the potential applied to the probe to know that of the surface.

The charging station, displayed in Figure 2, consists of a generator (Spellman) of DC voltage stabilized between 0 and ± 20 KV with reversible polarity controlled on the tip.

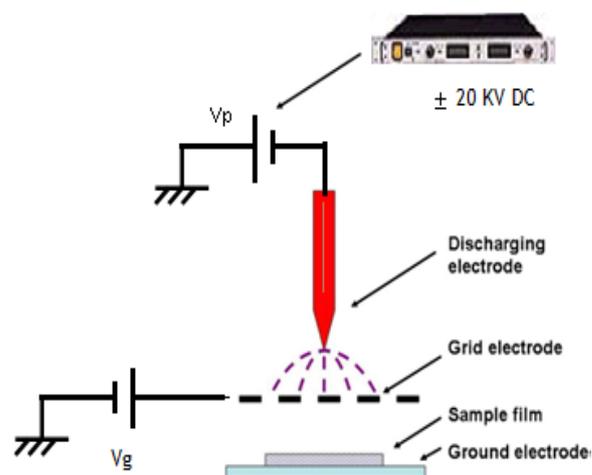


Figure 2. Charge station

The planar electrode is connected to the ground. With the aid of a microcomputer, the parameters of the discharge (time and value of the voltage applied to the tip) are fixed.

The corona discharge is obtained from a threshold voltage applied to the tip (of the order of -7 kV).

A grid electrode connected to the high tension generator is interposed between the tip and the surface of the sample. Its interest is twofold. On the one hand the deposit of charges is carried out in a homogeneous way on the surface of the sample, and on the other hand, it allows us to experimentally control the initial potential V_0 of the charge deposited on the surface of the material.

The measuring station consists of an electrostatic probe connected to a Trek-type digital electrostatic voltmeter (Figure 3)

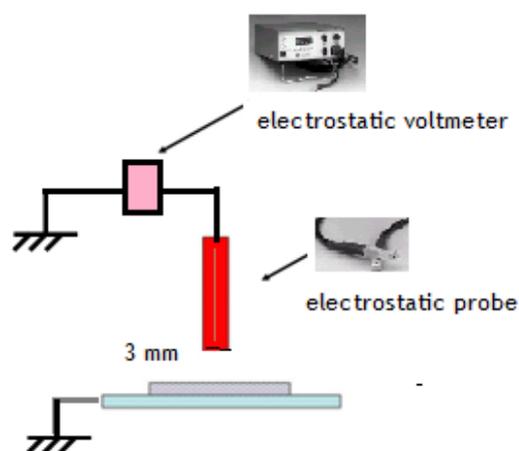


Figure 3. Measuring station

4. Description of the Samples

The polyethylene terephthalate "PET" is a thermoplastic that belongs to the family of polyesters. It is widely known under the trade name Mylar, Melinex or Hostaphan. PET is often used as dielectric in high-performance foil capacitor, or as an insulator for electric cables and electric motors coils. The PET samples used in the experiment were square sheets of 5 cm side-length and 0.5 mm thickness. One face of the samples was coated by silver paint so that

to ensure a good contact with the mirror-polished metal plate on which they were laid.

5. Results and Discussion

5.1. Initial potential effect V_0 :

Figure 4 shows the surface potential decay for different values of initial potential, fixing temperature and relative humidity at 55 °C and 50 % respectively.

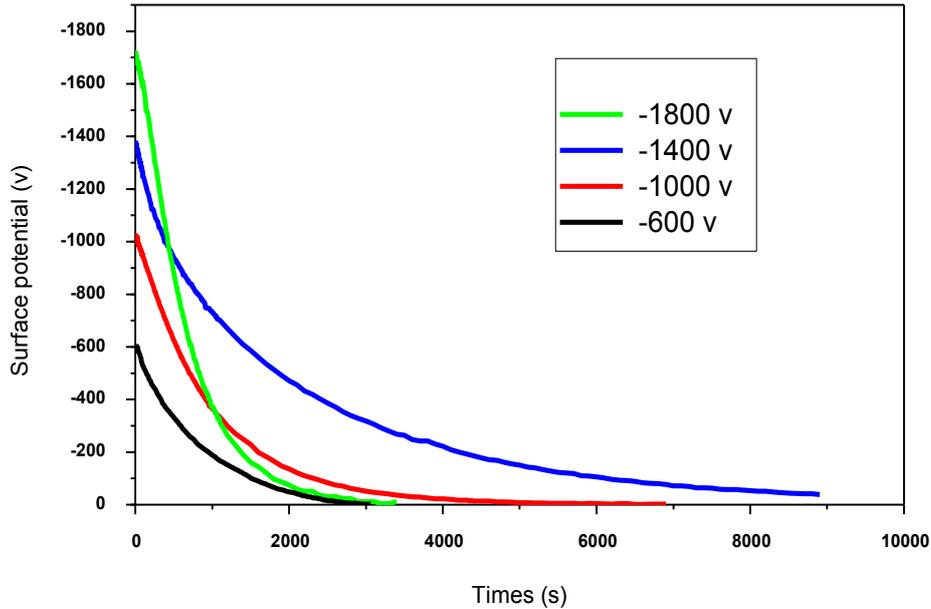


Figure 4. Surface potential decay as function initial potential V_0

We noted a strong dependence of the deposited charge density on the SPD evolution. Moreover, after some time, none of the charges remained on the sample surface.

To show the potential deposited effect on the sample surface, we represented the curves normalized to the initial potential V_0 (Figure 5).

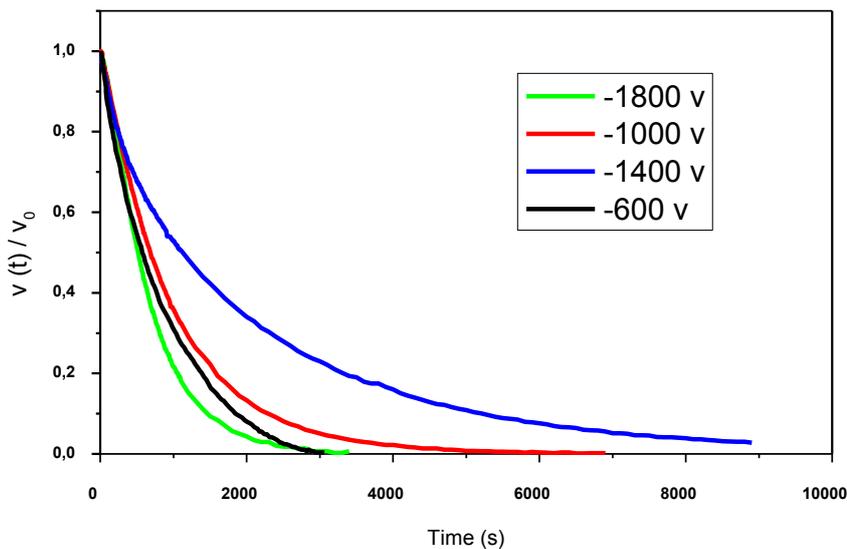


Figure 5. Characteristic $V(t)/V_0$

The results presented indicate that the curves are not superimposed. Two hypotheses may explain this result. When measurements were made on a single sample, then we can assume that the sample surface would progressively degrade by the corona discharges undergone on each deposit. This degradation implies a variation of the conductivity and therefore a change potential decay speed.

The second case, when virgin samples are used for each test (our case), then we can think about the existence of field effect on the material. We may think that the phenomenon related to the electron mobility (trapping -acceleration -trapping) will be more dependent on the field. An electron hops from a level of surface trap into the bulk is a charge injection dependent on the field and can assist the hop and then accelerate it in material. The charges then move under their own electrical field towards the grounded electrode.

Based on our interpretation, we found that the injection process can be observed for moderate voltages. It leads to explaining this phenomenon by the extremely pointed tip of the electrode that might

be the cause of the high electric field generation and easily inject a charge into the dielectric. This result goes hand in hand with the Baum work [20] which noted in his work on PET, a charge injection at low voltage values.

According to different models developed to explain the process of potential decay, it can be noted that if the model considers only shallow traps, the surface potential will reach zero over a few hours.

Therefore, we must assume the absence of deep traps to explain a decline that reaches the zero value. Hienz Von Segger's work [21] on PET showed the existence of two traps [22], [23], [24], shallow traps and deep traps. The structure of traps can be caused by chemical impurities, oxidizing products, chain breaks, molecules absorbed.

5.2. Deposit time effect $t_p(s)$:

The characteristics of surface potential of corona charged for different deposit time t_p are presented in Figure 6.

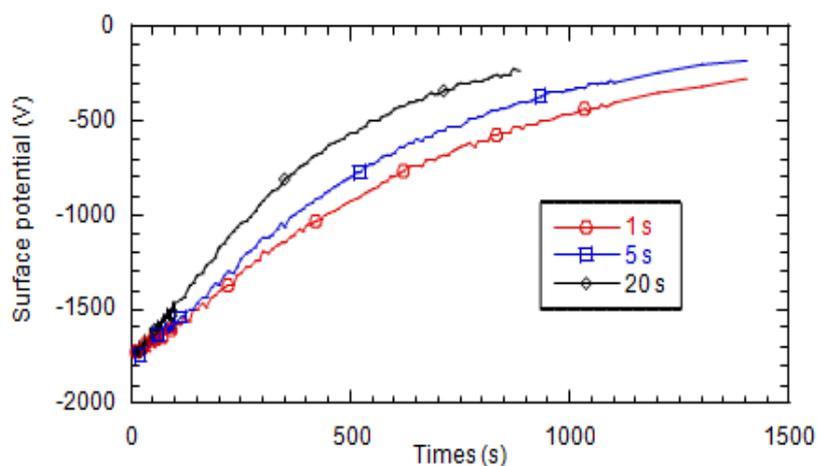


Figure 6. Surface potential of corona as function deposit time

The results provide an evidence for the importance of the charging condition and particularly the charging time. It is observed a difference in decay rates.

The experiment clearly illustrates that the corona discharge can not only deposit electric charges on the surface of the polymer. It can also have a noticeable impact on the decay characteristics when a corona source is employed.

Additionally, several features are noted. The nature of the decay is shown as depending on the deposit of initial potential and the presence of incident light on the surface samples during charging leading to a much more rapid decay of charge.

Perhaps, the light from the corona discharge plays the most important role in negative charging by inducing more rapid charge decay. It is suggested that the light aids the injection of electrons from

surface states into the bulk. Furthermore, it would appear that the fast decay is caused by photo-injection of electrons from the PET surface states into mobile bulk states induced by the corona discharge light.

This deduction leads to assume that the photon energies play an important role in facilitating the decay of charge.

The charge injection requires a certain energy to make the large gap of the insulator pass through the loads and bring it from Fermi level surroundings to levels close to traps where the charge can have a certain mobility. However, it is known that the corona discharge is capable of supplying this energy to certain carriers.

This, therefore, suggests that the corona discharge can not only deposit an electrical charge on the surface of the insulator, but also can play an

important role in the evolution process of the surface potential decay.

The corona discharge produces CO^- , OH^- , O^- , O^{2-} ions, and also neutral species with vibrated or electronic excited states. The work of Baum et al [25], [26] has demonstrated the role of ions and excited neutral gas molecules, present in the air surrounding, the corona discharge in the charge injection for the polyethylene samples charged by negative corona discharge. By means of a breath of air applied to the drift zone, which prevents the neutral species from reaching the surface, the cross-over is eliminated, and thus the charge injection.

The injector effect of the corona discharge from the deep surface states to the shallower volume states has also been highlighted [27], and it is subsequently carried out in the Perlman team in Quebec. It has been shown that the neutrals of the negative corona discharge [28] play the role of injector.

Haridoss et al [29], also identify neutral species as vibrational excited states of NO, and excited electronic states of N_2 and can also be O_2 .

It is possible to mention that corona light and possibly photon energy play an important role in the charge flow process on the surface of the insulator. It should be also pointed out that light causes electron photo-injection from surface states in volume states. The photons generated in the corona discharge would probably be a support and a plus to the initial charges deposited in the deep surface states to inject into the volume states where they become mobile. This leads to a rapid decline in surface potential.

We, therefore, retain the effect of the corona discharge, on the surface of the PET, the role of the ions, the excited neutral gas molecules, present in the discharge zone, and probably, the photo-injection of the charge carriers in the volume of the material [29].

Even in the absence of this activation by the corona discharge, an injection of the electron is not excluded, it is rather a very likely phenomenon in polymers.

This study also revealed the existence of the "Cross-Over" phenomenon (Figure 4). In fact, after the same time of measurement, the potential decay of the sample charged with -1800 V is more significant than -1400 V, -1000 V and -600 V.

This cross-over phenomenon has been already observed by several authors [10], [14], [30], [31]. It indicates a charge injection into the bulk of the material.

We also observed a high initial growth rate followed by a slower value. The strong initial decrease may be due to the injection of charges deposited under the field effect created by their own charges. Cross-over phenomenon can be attributed

to the fact that the injected charge is dependent on the deposited charge quantity. This decay may be explained by a total injection of the deposited charges on the dielectric surface under the electrical field generated by the charges themselves. When the injected charges are subject to local field this will lead them to the sample back face.

This hypothesis may be explained by the existence of two linear phases of the surface potential decay curve; a linear phase which corresponds to the movement of charges through the material and a second phase corresponding to the charges leaving the material.

Molinié [32], [33], [34] pointed out the existence of a link between the potential decay and the absorption current. Knowing that in the case where the volume polarization phenomenon is the only mechanism or the predominant mechanism responsible for the charge evolution deposited on the insulator surface by corona discharge; the absorption current should decrease following a power law according to form:

$$I_{abs} = At^{-n} \quad (2)$$

And the potential derivative follows a law of the type:

$$\frac{dV}{dt} \propto (t)^{-n} \quad (3)$$

Which causes proportionality between the absorption current and dV/dt . The decay rate dV/dt is a convenient means to show the conduction intervening nature at charges deposition.

5.3. dV/dt transformation:

Presentation in bi-logarithmic coordinates is proportional to a current and, is an appropriate mean to explain the most probable mechanism taking place in the charge flow process insulating surface. To establish the link between potential decay and absorption current, which are linked principally to a low polarization mechanism of material, Molinié [32] has shown in his work on epoxy resin that the material polarization mechanism gives an absorption current according to Curie-von Schweidler law. According to the same author, the curve linearity of potential decay which follows the power law of $dV/dt \propto (t)^{-n}$ type was assimilated to absorption current. This, therefore, suggests polarization phenomenon predominance of surface potential decay in this material. On the other hand, Von Berlepch [35] and Bigarré [36] have observed in their study on the polyethylene from this representation two straight lines with different slopes on either sides of mean transit time value τ .

dV/dt characteristics relating to the curves of Figure 4 are displayed in Figure 7.

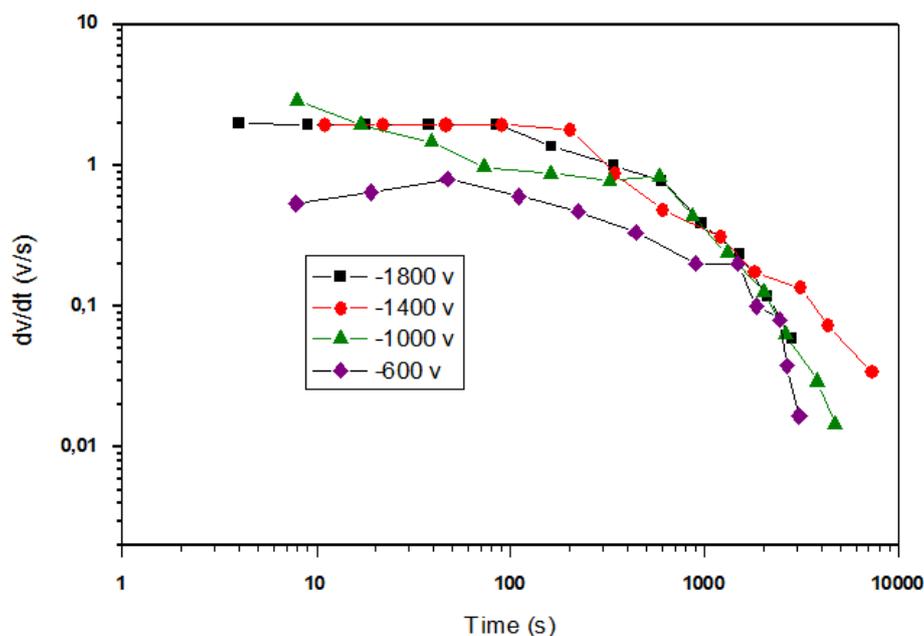


Figure 7. Log (dV/dt)-vs-Log(t) for various initial potential

We note a cross of two straight lines with different slopes. This, therefore, confirms the absence of a prevalent dipolar polarization and corresponds rather to the existence of two modes of surface potential decay regimes separated by a transit time τ .

This time corresponds to a slope change on the rate decay evolution as function of time.

Transit time:

$$\tau(-1800\text{ V}) = 85\text{ s}$$

$$\tau(-1400\text{ V}) = 202\text{ s}$$

$$\tau(-1000\text{ V}) = 582\text{ s}$$

$$\tau(-600\text{ V}) = 1480\text{ s}$$

Von Berlepsch [35] observed this representation in studies on polyethylene a slope change which is attributed to the existence of two regimes of surface potential decay separated by a transit time which represents the transition charge to the back face. We can see on the curves derivative dV/dt a shape quite conforming to injection models [36], [37].

Particularly, a charge injection [37], [38], [39], [40] based on the charges geometric motion in the material with density and mobility of constant charge.

Therefore, it is possible to determine the charge carry mobility in the material after having been deposited on the surface for $T < \tau$ [41], [42].

This mobility is expressed:

$$\mu = \frac{L^2}{V_0 \tau} \quad (4)$$

L : the insulating material thickness.

V_0 : the initial potential.

τ : the transit time.

Extrinsic electron mobility:

$$V_0 = -1800\text{ V}$$

$$\mu = \frac{(0,5 \times 10^{-3})^2}{1800 \times 85} = 1,633986 \cdot 10^{-12} \text{ m}^2/\text{V}\cdot\text{s}$$

$$V_0 = -1400\text{ V}$$

$$\mu = \frac{(0,5 \times 10^{-3})^2}{1400 \times 202} = 8,840169 \cdot 10^{-13} \text{ m}^2/\text{V}\cdot\text{s}$$

$$V_0 = -1000\text{ V}$$

$$\mu = \frac{(0,5 \times 10^{-3})^2}{1000 \times 582} = 4,295532 \cdot 10^{-13} \text{ m}^2/\text{V}\cdot\text{s}$$

$$V_0 = -600\text{ V}$$

$$\mu = \frac{(0,5 \times 10^{-3})^2}{600 \times 1480} = 2,815315 \cdot 10^{-13} \text{ m}^2/\text{V}\cdot\text{s}$$

Figure 8 shows the mobility evolution for different values of V_0 relating to the curves in Figure 8.

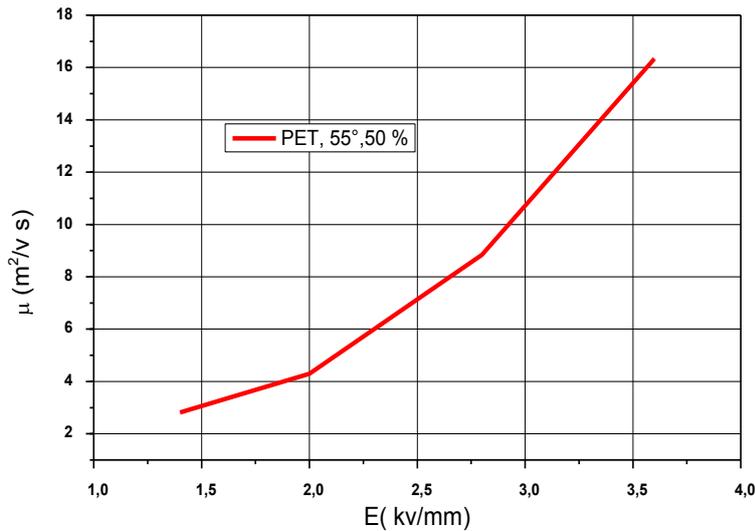


Figure 8. Mobility depending on the field applied during the transit time.

The mobility increases with the electric field.

This seems quite relating to the field dependence. Moreover, we plotted in Figure 9 the

inverse of the transit time evolution ($1/\tau$) as a function of E/L in log-log coordinates.

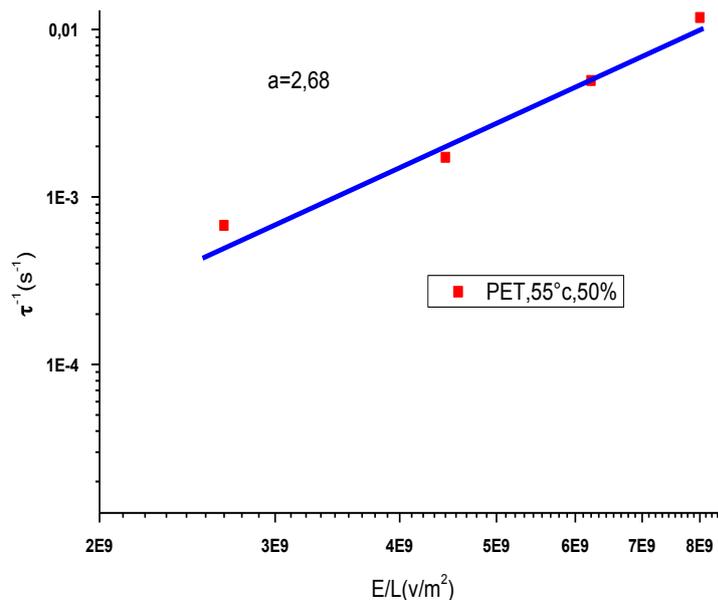


Figure 9. Log-log inverse curve of the transit time as a function of E/L

We note a slope around 2.7. According to [36], [43], [44] this shows a rather dispersive transport governed by a hopping process between distributed energy sites. This calculation allows us to confirm the initial hypothesis on the mechanism dominating the charge flow in the insulating material inverse of the transit time as a function of E/L .

6. Conclusion

The surface potential decay characteristic of corona charged PET has been analysed in terms of a theory that assumes injection into the bulk of the charge deposited on the surface and that would account well for the curves in representation dV/dt .

The amount of charge injected depends on the initial potential value.

Charge plane model based on the geometric movement charges in the material with the assumption of constant charge mobility can be applied to our experimental results of Surface Potential Decay.

This interpretation lends particular interest to mobility and how it depends on the field. The graphical representation of the mobility suggests a rather dispersive transport governed by a process of hop in sites distributed in energy.

Finally, this study has demonstrated the importance of the experimental methodology for

evaluating the physical phenomenon that governs the potential decay. We suggest that this technique of Surface Potential Decay may open multiple way for the evaluation of the state aging of the insulating materials.

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Authors' Biographies



Dr. Karima SMILI. is an associate professor teaching at the Higher School of Industrial Technologies, and a researcher at the Laboratory of Electromechanical Engineering, Annaba, Algeria.

She graduated from the University of Badji Mokhtar, Annaba, Algeria in 1998 where she received her diploma in electromechanical engineering.

She earned her magister degree in 2001 and her doctorate degree in 2018 from Badji Mokhtar, Annaba University, Algeria.

Her major research interests include: partial discharge, dielectrics materials characterization and electrostatics .
e-mail adress: k.smili@esti-annaba.dz



Pr. Lazhar Herous. After graduating from the Faculty of Electrical Engineering, Badji Mokhtar, Annaba University, Algeria, in 1982. He obtained the Magister degree in 1988. In 2006.

He earned his PhD degree on the topic of neutralization of the electrical charge deposited by corona discharge on an insulating surface.

Five years later, he was appointed Professor of Electrical Engineering at the Faculty of Science and Technology, University of Badji Mokhtar, Annaba, Algeria.

Pr. Herous is currently teaching at the University of Annaba and a researcher at LGEG laboratory.

He is the author of numerous articles published in international journals and a member of the scientific board.
e-mail adress:lherous@yahoo.fr