

# Apparent Mobility and its Relationship with Ageing in Polymeric Insulation Materials

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**Abstract--Apparent mobility obtained from space charge decay measurement has been recently used as an ageing marker to assess degradation of the insulation materials. The apparent mobility of charge carriers becomes slower after experiencing electrical ageing. In this paper, we have measured space charge decay in polymeric insulation material using the pulsed electroacoustic technique and studied apparent mobility features in a wide range of the applied fields and poling times. It has been found that the increase in the applied field and poling time produces more deep trapped charges, leading to a decrease in apparent mobility with time. For a specific time, the detrapping process is dominated by the charges of specific trap levels, resulting in a time dependent apparent mobility. In addition it has been found a sudden increase in apparent mobility at high fields, indicating that a precaution has to be taken when assessing the ageing using the method.**

**Index Terms--space charge, apparent mobility, polymeric insulation, electrical ageing, high electric field, trapping characteristic.**

## I. INTRODUCTION

Polymeric materials are widely used as electrical insulation due to their excellent properties. However, their long term performance is often hinted by easy formation of space charge in the materials, especially in the presence of high electric fields. At high fields charge can be injected into the material and some of them will be trapped. These trapped charges in the material result in electric field enhancement in one region and reduction in other region. In addition, the trapping and detrapping processes involve energy exchange with the material and could lead to degradation of the material. The change in material either physically or chemically will modify its trapping and detrapping characteristics. Ultimately, this may lead to failure of the insulation. Consequently, the diagnosis of the insulation status is very important for maintenance and replacement of power equipment. Apparent mobility, a parameter obtained from space charge measurement, has been proposed as an ageing marker for dielectric materials [1].

In the present paper we intend to explore the suitability of the proposed parameter as an ageing marker over a wide range

of the applied fields and poling times in low density polyethylene (LDPE) insulation. Space charge profiles were monitored using the pulsed electroacoustic technique (PEA).

## II. THEORETICAL BACKGROUND

Recent developments in the space charge measurements have opened an avenue to profile the space charge inside the materials non-destructively. Investigation on the volume density of space charge during the polarization (the application of a poling field in a given time) as well as the depolarization (removing voltage and grounding both electrodes) as a function of time has been extensively carried out, resulting in many publications. Further exploration based on space charge measurements has resulted in the estimation of apparent charge mobility [1]. From the charge profiles obtained, the mean value of net charge density  $q(t; E_p)$  stored in the specimen can be evaluated as the integral of the charge in absolute value along the sample thickness L:

$$q(t) = \frac{1}{L} \int_0^L |q_p(x, t)| dx \quad (1)$$

When the applied field is removed and the electrodes are short-circuited, the amount of charges in the insulation decreases with time due to the detrapping process and recombination. Consequently, there is a current flowing in the external circuit.

The charge continuity equation across the sample thickness ( $x$  direction) for a flat dielectric sample with a permittivity of  $\epsilon$  placed between the plane parallel electrodes, short-circuited after poling at a given voltage,  $V$ , for a time  $t_p$ , can be written as:

$$J_T(t) = J_C(x, t) + \epsilon \frac{\partial E(x, t)}{\partial t} = \rho_f(x, t) \mu(t) E(x, t) + \epsilon \frac{\partial E(x, t)}{\partial t} \quad (2)$$

where  $J_T(t)$  is the total discharge current density,  $J_C(x, t)$  the conduction contribution,  $\rho_f(x, t)$  the volume density of free charge carriers,  $E(x, t)$  the local electric field and  $\mu(t)$  the mobility which is considered as constant in space.

For the same system, the Poisson equation is

$$\epsilon \frac{\partial E(x, t)}{\partial x} = \rho_f(x, t) + \rho(x, t) \quad (3)$$

where  $\rho(x, t)$  is the volume density of trapped charges.

Substitute  $\rho_f(x,t)$  in equation (2) by (3) and integrate the expression along x-axis from  $x=0$  to  $x=L$

$$\mu(t) = \frac{J_T(t)L - \varepsilon \frac{\partial}{\partial t} \int_0^L E(x,t) dx}{\varepsilon \frac{[E(L,t)]^2 - [E(0,t)]^2}{2} - \int_0^L \rho(x,t) E(x,t) dx} \quad (4)$$

The mobility expression is quite complex and cannot be applied directly to the results of space charge measurements. In practice, the charge density profiles are contributed by the free and trapped charge density. However, in the model, it is assumed that both free and trapped charges have an associated mobility. Therefore, under this assumption, the detrapped charges can be regarded as the free charges of low mobility. In insulation materials such as polyethylene, due to the high density of traps in various depths, it can be assumed that during the polarization procedure, the trapped charges are much more than the conduction ones. It means that  $\rho \gg \rho_f$ .

Therefore, the detrapping process is dominant in the discharge current conduction. Moreover, the following assumptions can be used for simplifying the formula:

- The recombination process can be neglected. Thus, from the charge conservation law:

$$J_T(t) \cong Ldq/dt$$

where  $q(t)$  is the mean density of total charge measured.

- The charge is uniformly distributed within the insulation. It means  $\rho(x,t) = \text{constant}$  along  $x$

-  $\partial E / \partial x = 0$  for the charge which is concentrated near the electrodes. In other words, the electric field  $E(x,t)$  is equal to the field on the electrodes. Therefore, from Gauss theorem, the field is  $E(x,t) = q(t)L/2\varepsilon$

From these assumptions, the model has been proposed with a very simple expression of mobility:

$$\mu(t) = -\frac{2\varepsilon}{q(t)^2} \frac{dq}{dt} \quad (5)$$

The evaluation of mobility is based on the detrapping process of space charge, thus it is called the trap-controlled mobility. It has been claimed that in spite of the considerable assumptions, the model provides the basis for estimating the mobility which is a significant parameter in the space charge dynamics as well as in the comparison of ageing process of the industry insulation materials. However, the proposed method was only validated by a few specific experiments at poling fields of 150kV/mm and 80kV/mm for 1 hour poling time.

### III. EXPERIMENT RESULTS

When the applied field exceeds a threshold value charge injection occurs. This phenomenon can be clearly seen when the applied field is removed. In addition, the space charge profile and its change with time provide information on charge detrapping and transportation in the bulk.

LDPE samples with 180  $\mu\text{m}$  thickness were stressed at 3, 5, 7, 9 and 11 kV for 15, 30 and 60 minutes. All the space charge measurements were performed using the pulsed electroacoustic technique [2] at room temperature. Figures 1-

3 show the selective space charge profiles obtained at different times by short-circuiting electrodes after poling the specimen at the applied voltages for a given time.

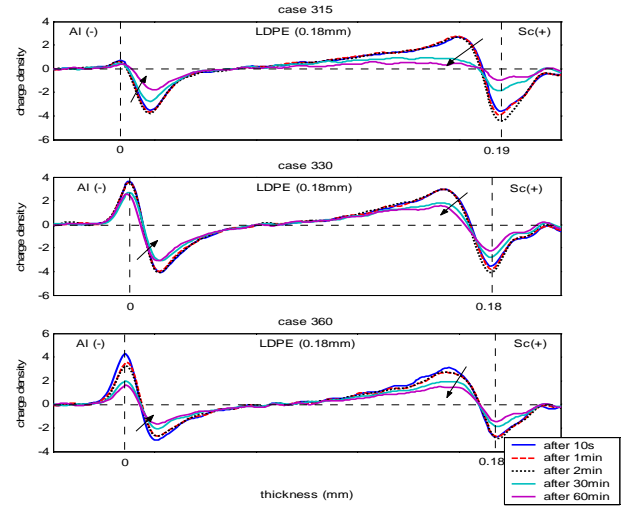


Figure 1 Charge profiles after the removal of applying voltage of 3 kV for 15min, 30min and 60min poling.

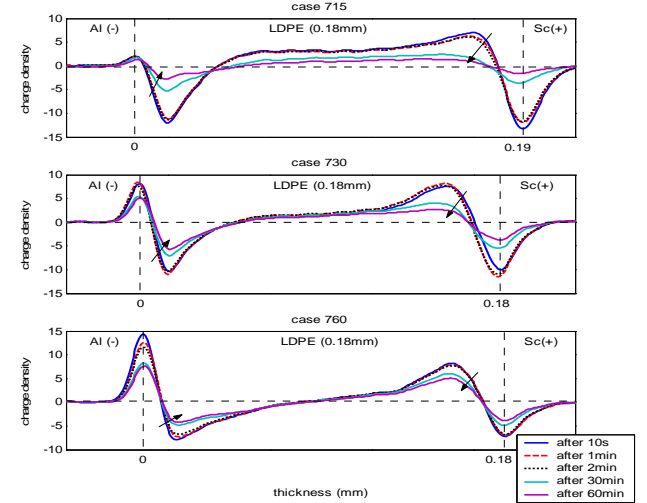


Figure 2 Charge profiles after the removal of applying voltage of 7 kV for 15min, 30min and 60min poling.

The presence of homocharge after the removal of the applied voltages suggests the charge injection from the electrodes. At 3 kV, charge profiles changes slightly with the poling times. More importantly, the charge decay rates are closely related to the poling times. For a short poling time charge decay is much faster compared with a longer poling time. At 7 kV, the amount of charge present in the bulk is more compared with that at 3 kV. Charge profiles change significantly with the poling times. Positive homocharge dominates the bulk for a short poling time while charge distribution becomes more symmetrical for a longer poling time. For charge decay, it shows a similar fashion to that at 3 kV. However, when the applied voltage is increased to 11 kV charge dynamics are very different from those at lower voltages. Charge distribution starts with a symmetrical with a short poling time and changes to an asymmetrical for a longer poling time. In addition, the amount of charge stored becomes

for a longer poling time, indicates a complicated charge movement at higher applied voltage. It has been noticed that the charge decay shows a totally different behaviour from that at low applied voltages, i.e. faster at a short poling time and slower at a longer poling time.

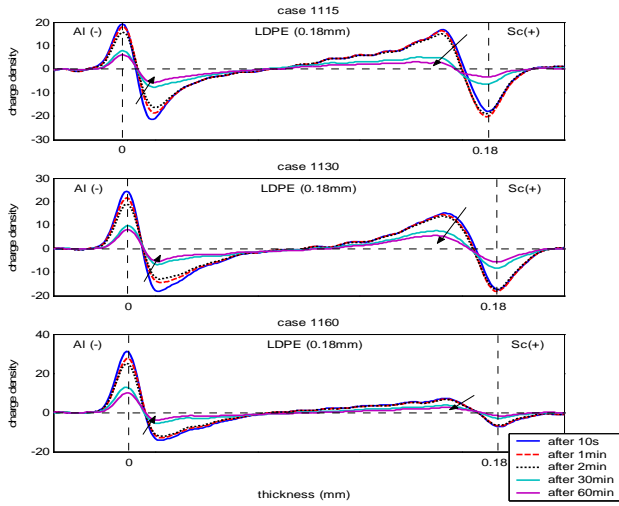


Figure 3 Charge profiles after the removal of applying voltage of 11 kV for 15min, 30min and 60min poling.

#### IV. APPARENT MOBILITY

The space charge profiles obtained during the volt-off procedure can be used to calculate the mean charge density of total accumulated charges using above equation (1). Based on the charge decay measurements at different times, the time dependent charge density can be obtained for different poling times after the removal of the different applied fields.

Figures 4 - 6 show the corresponding total charge dependence on time during the depolarization process. Generally, one can see that the mean charge density  $q(t)$  decreases with time monotonically.

If one can find the derivative of discrete points then the charge carrier mobility can be estimated directly using above equation (5). Unfortunately, it is not easy to get the derivative of discrete points. One solution to the problem is to use a fitting curve for these discrete points. In order to get a best fitting curve, the most important step is to guess the type of function describing the curve correctly. The describing function is usually based on the physical meanings of the problem. This is the most difficult point because until now there is not any analytic function which presents the dependence on time of the total charge inside the polymeric materials. Although there have been a lot of published papers on the charge mechanisms inside the polymers, all of them only concentrate on analyzing the experimental results and explanations.

Various approximations have been tried. It has been found that the decay based on the power law [3] gives a reasonable approximation. In addition, when plotting in terms of log-log, the charge density decays with time almost linearly in a broad

region. By linearising the characteristics, the power function can be obtained:

$$\ln q = a + b \ln t \quad (6)$$

To fitting the data more accurately, the following power fitting function is proposed:

$$\ln q = a + b \ln(t + c) \quad (7)$$

or 
$$q(t) = a(t + c)^b \quad (8)$$

where  $a$ ,  $b$ ,  $c$  are coefficients which often hold only for a given time range.

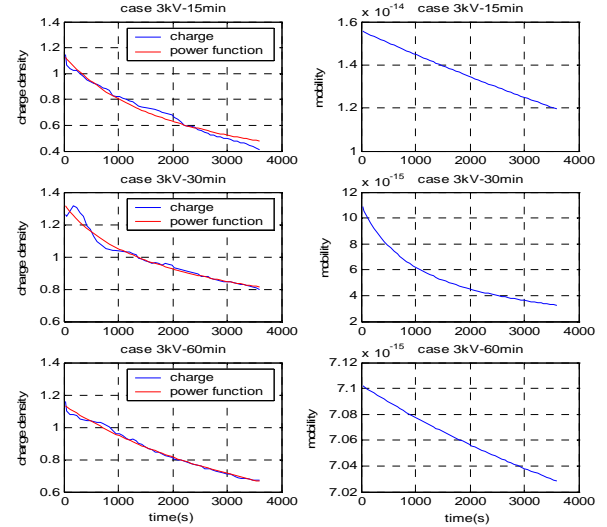


Figure 4 Charge density power function fitting curve and its mobility, poling at 3kV for 15min, 30min, and 60min.

Figures 4 - 6 show also the dependence on time of charge carrier mobility resulting from the power fitting function (equation 8). Generally, the apparent mobility decreases with time. This is consistent with the observation in [xx]. The possible reason for this is that the charges in shallow traps detrapp more easily, resulting in a high mobility while charges in deep traps take a longer time to detrapp, leading to a low mobility.

At 3 kV the obtained mobility tends to decrease with the increase with poling time. The decay rate changes with the poling time. For a shorter poling time the mobility decreases fast. The exact mechanisms are unknown. If one accepts that the apparent mobility can be used as an ageing marker, the change in mobility observed may indicate the effect of applied field on material degradation. Alternatively, the observed change in apparent mobility may simply reveal a process that injected charge carriers transfer from shallow traps to deep traps when poling time is extended. At 7 kV, the apparent mobility shows a similar trend to that at 3 kV. However, the decay rate is slightly slower. In addition, the apparent mobility value is lower at 7 kV. The value at 5 kV sits in between although not shown here due to the limit of space. The above two possible explanations can still be applied here. The decrease in the apparent mobility with the applied voltage may be caused by ageing as the influence of high voltage on degradation of the material would be severer, i.e. causing

formation of deep traps. Consequently, a lower mobility is observed. On the other hand, it may indicate that a high applied voltage can assist injected charges to fill deep traps existing in the material. Another possibility is the combination of both. Further research is required to underpin the mechanism.

At 11 kV, the initial apparent mobility value no longer follows the previous trend. Its value is higher than that at lower applied voltage. This actually starts at 9 kV. There is no much difference between poling time of 15 and 30 minutes. By examining the charge distribution profiles in Figure 3, it is believed that this type of behaviour is closely related to the recombination caused by high amount of bipolar charge injection.

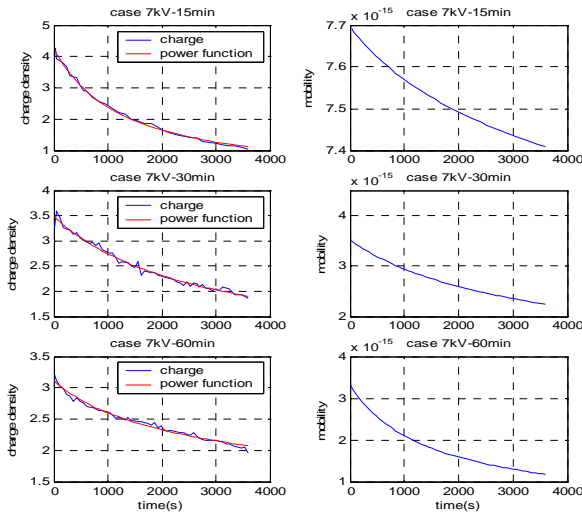


Figure 5 Charge density power function fitting curve and its mobility, poling at 7kV for 15min, 30min, and 60min.

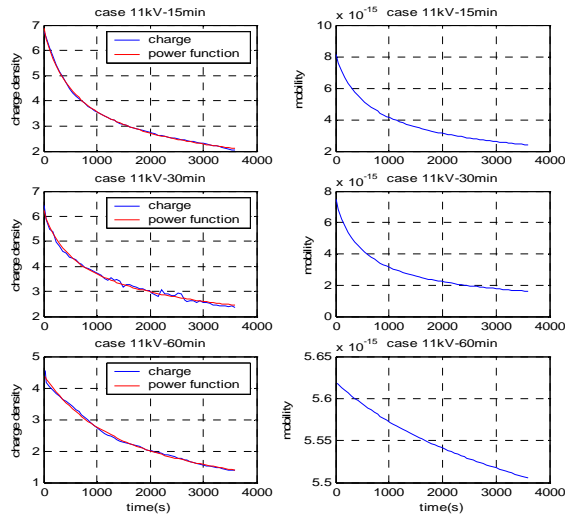


Figure 6 Charge density power function fitting curve and its mobility, poling at 11kV for 15min, 30min, and 60min.

Mobility is a very important parameter, especially in the power cable industry. The decay rate of accumulated charges inside the polymer is the signal from a material from which one may derive information about the status of the insulation.

The apparent mobility is, therefore, used as a marker for the insulation degradation by comparing the decay rates [26]. The fast decay of stored charges is necessary to avoid the failure of system due to the breakdown. If this purpose is required, the model proposed (equation 5) can provide the acceptable reliability. However, the model is based on a lot of assumptions, so there are certain limitations. For example, one of the proposed assumptions is the neglect of recombination in the material. Nevertheless, at high fields, the recombination of oppositely charged species is considerable. This has been confirmed by our research. The model also assumes that the charge is uniformly distributed within the insulation. In fact, the obtained space charge profiles show the dependence on the electrode materials of charge distribution as well as the difference in distribution over the thickness of sample. Moreover, there is the recombination area inside the polymer. As a result, this assumption is not correct. However, it can be observed that the shape of charge distribution remains nearly unchanged. If the functions which describe the distribution of positive and negative charges over the thickness of sample can be obtained separately, they can be assumed constant during the time. The model then can be solved based on these separate functions. The above ideas are only suggestions to improve the accuracy and reliability of the model, but their success and efficiency require the further research on the space charge dynamics.

## V. CONCLUSION

Our investigation of apparent mobility over a wide range of the applied fields and poling times reveals that care has to be taken when using it as ageing marker of the insulating materials as some of the assumptions are no longer valid. Following conclusions can be drawn from the present study.

The apparent mobility shows a good behaviour at fields less than 40kV/mm. Generally, it decreases monotonically with time. At the same applied field, the apparent mobility becomes smaller with poling time. On the other hand when the poling time is fixed the apparent mobility decreases with the poling fields.

Above the threshold field the recombination may play an important role in the reduction of charge density due to strong field enhanced charge injection. This invalidates the assumption made in order to simplify the estimation of the apparent mobility. It is, therefore, necessary to carry out more research to improve some of impractical assumptions and develop a better model for the mobility estimation.

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