The Missing Link – The Role of Space Charge in Polymeric Insulation Lifetime

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***Abstract*—Polymeric insulation in power equipment experiences degradation and ageing under service conditions. The determination of remaining life plays a key part in the asset management. This requires an ageing indicator which can be used to monitor the status of the insulation. In this paper a simple model based on trap creation has been proposed and a concept of critical trap density can be used to describe the lifetime of the insulation. Assuming the power law relationship between the trap creation and the electric field, the empirical inverse power law can be derived. This allows one to relate the physical mechanisms and ageing processes (trap generation). Since the number of traps and energy depth of traps have direct influence on charge dynamics, using the two energy levels of trap depth model developed previously it is possible to estimate the trap density through changes in space charge dynamics. Further work is necessary to establish the direct relationship between trap density and the remaining life of the polymeric insulation.**

Keywords: polymeric insulation, degradation/ageing, space charge, charge trapping, trap generation, trapping model.

I. INTRODUCTION

Space charge and its influence on electrical performance of dielectric materials have been recognised for many years. Progress made in non-destructive charge measurement techniques has allowed researchers to directly observe space charge phenomena in polymeric insulation. The abundant experimental data gathered over the last twenty years has propelled modelling of charge dynamics including charge generation, transport, trapping/detrapping and recombination in polymeric insulation and significantly improved our physical understanding of space charge.

Polymeric insulation in power equipment experiences degradation and ageing under service conditions. The economic consideration and market competition will lead to an increase in the operating electric field. The high electric field phenomena in polymeric insulation suddenly change from scientific pursuit to practical importance, as the role of space charge dynamics becomes increasingly significant in determining electrical performance of the material [1]. Preventing unforeseen outages of power transmission and distribution needs fully understanding ageing of polymeric insulation. Over the years, lots of efforts have been made to develop ageing models from different viewpoints. However, there has been an ongoing debate on the role of space charge in electrical ageing, i.e. is space charge the cause of ageing or the consequence of ageing?

In the present paper, it is author's intention to develop a simple ageing model that has significant physical meanings but more importantly the model should have a clear indicator that allows one to estimate the remaining life of the polymeric insulation.

II. EMPIRICAL INVERSE POWER LAW

A model that correlates the lifetime of insulation to the applied electric field has been a subject of much debate in the literature over the years. Earlier work (including long term constant low field stress at various temperatures) on various dielectric materials showed substantial evidence in support of the inverse power law of the lifetime $t \propto E^{-n}$, where t is the lifetime, E is the applied electric field and n is the power index related to the material.

Weibull distribution has been used to process the failure data for short-term electrical breakdown and long-term failure time. When these two factors are combined together, the following form of Weibull distribution is often used:

$$p(E,t) = 1 - \exp\left[-\left(\frac{E}{E_0}\right)^a \left(\frac{t}{t_0}\right)^b\right] \quad (1)$$

where E_0 and t_0 are the characteristic breakdown strength and failure time of the material, a and b are two constants related to the material. For a constant probability of survival we have the inverse power law:

$$t = kE^{-n} \quad (2)$$

where k is a constant related to the material and $n=b/a$.

Even though the Weibull distribution does not offer any physical mechanisms of electrical ageing, it has been considered as the foundation of the empirical inverse power law. In reality, engineers would always like to have equations that allow them to simply predict the lifetime of the dielectric material at operating electric field from the time obtained at accelerating electric field (much higher than the operating electric field). The inverse power law allows them just to do that. Consequently, it has been widely used in the insulation design for high voltage equipment and electronic devices. However, there are two issues with this practical approach. Firstly, there is no any evidence to support the assumption that at low operating electric field, the dielectric will indeed fail in the same form as that at high

electric field which is inexplicitly assumed when applying the inverse power law. In literature some other types of distributions have been used to characterise the failure, indicating that the inverse power may not be the only form that describes the lifetime of insulation materials. Secondly, the inverse power law does not tell the degradation/ageing mechanisms. To limit/reduce the degradation of the insulation and manage lifetime of the insulation it becomes essential to understand what are the key components that affect material degradation processes and how to characterise ageing.

III. Existing Ageing Models

Early in 1948, Dakin [2] proposed a life time ageing model of insulation materials based on chemical reaction rate theory. In Dakin's model, the lifetime of an insulation system can be expressed as:

$$L = f'(p_L)\exp\left(\frac{B}{T}\right)/C \qquad (3)$$

where, L is the lifetime, T is temperature, $\mathrm{f}'(\mathrm{p_L})$ is a function which reflects the end-up point of insulation corresponding to the selected property $\mathrm{p_L}$. B could be understood as an activation energy and C is constant.

Based on Dakin's lifetime model, Crine [3] proposed that with the electrical and mechanical stresses attending, the height of activation energy will be modified by work deformation W. Thereafter in [4], Parpal and Crine introduced the concept of submicrocavities (collection of many holes) for electrically-accelerated ageing model under the ac stress. In terms of work deformation W under ac stresses, it equals to qλE, where q is unit charge amount, λ is deformed distance of molecular chains and E is the applied field. Considering forward (breaking interchain bonds) and backward (rebounding of intermolecular chains), the time from the original state to the final state of ageing is:

$$\mathrm{L} = \frac{\mathrm{h}}{kT}\exp(\frac{\Delta G}{kT})\mathrm{csch}\,(\frac{\mathrm{q\lambda E}}{kT}) \qquad (4)$$

where h is Planck's constant, k is Boltzmann constant, and ΔG is activation energy barrier, i.e. free energy difference between reactant state G_1 and G_m, which is the free energy at the top of the barrier separating the reactants from the products state G_2, as shown in Figure 1.

In [5], Lewis proposed a model on ageing stating a chemical kinetics between two molecular entities R_a and R_b. In his theory, original of bonding (state 1) between R_a and R_b will be ruptured and reformed into a new entities system (state 2). As shown in Figure 2, Lewis defined that the activation of forward transition from state 1 to state 2 and backward transition from 2 to 1 as: $\Delta G_1 = G_\mathrm{m} - G_1$ and $\Delta G_2 = G_\mathrm{m} - G_2$. Therefore, the lifetime L of Lewis model can be expressed using forward transition rate $\mathrm{k_{12}}$ and backward rate $\mathrm{k_{21}}$:

$$\mathrm{L} = (\mathrm{k_{12}} + \mathrm{k_{21}})^{-1} = \frac{\mathrm{h}}{kT}[\exp\left(\frac{-\Delta G_1}{kT}\right) + \exp\left(\frac{-\Delta G_2}{kT}\right)] \qquad (5)$$

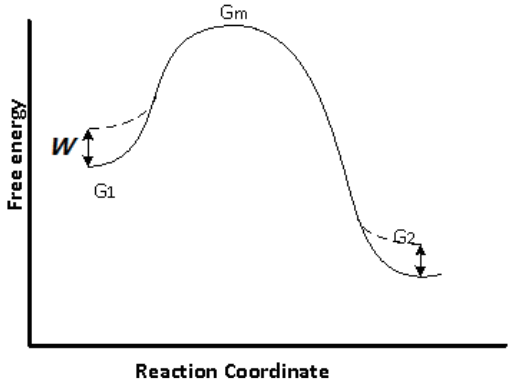

Figure 1 Schematic energy diagram for Crine's model.

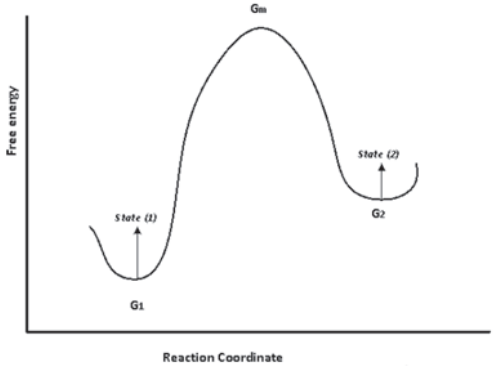

Figure 2 Free energy diagram of double well potential used in Lewis model (DMM model as well).

It should be recognized here that standing at perspective of Lewis's model, Dissado-Mazzanti-Montanari (DMM) model as well, the free energy of aged state G_2 should be higher than unaged state G_1 due to an input of energy into material [5-8]. However, this conflicts with viewpoint from Crine [3, 9] who considered the free energy should decline from unaged state to aged state. It is claimed by Crine that $G_2 > G_1$ is impossible to occur because it indicates the activation energy required for aged state back to unaged state will be smaller than the activation energy for ageing direction [10]. This, in Crine's consideration, suggests that ageing will never happen.

The DMM model was initially proposed for dc stresses [6, 11] and subsequently extended into ac condition [11]. The model, which shares the same thermo-kinetic background with models from Crine's and Lewis', is based on degradation rate of insulation system under electrical and thermal stresses. What different from previous models, DMM model takes consideration of space charge factor, which will accumulate to cause local stress enhancement and thereby lowering the energy barrier with the release of stored eletromechanical energy. By considering impact of space charge, the lifetime in DMM model can be written as:

$$\mathrm{L} = (\mathrm{k_{12}(E)} + \mathrm{k_{21}})^{-1}\ln\,[A(E)/(A(E) - A^*)] \qquad (6)$$

where A is defined as a equilibrium value of products proportion (state 2), which $A = \frac{k_{12}}{k_{12}+k_{21}}$, and A^* is a fraction value converted when the insulation life terminates. And $A(E)$ and $k_{12}(E)$ are values under local space charge field E. $k_{12}(E)$ can be expressed in form:

$$k_{12}(E) = \frac{kT}{h}\exp\left[-\Delta G_1 - \frac{C_2' E^{4b}}{kT}\right] \quad (7)$$

where C_2' and b are both constants.

IV. New Ageing Model

It has been stressed that space charge plays a crucial role in the material degradation processes. The impact of charge dynamics can lead to the generation of new traps which is not obvious in the above models. Actually, the generation of new traps has been considered as one of the mechanisms that cause failure of dielectrics in electronic devices [12]. It has been proposed that a degradation process that leads to eventually final breakdown includes the following steps: The stress (temperature, electric field or current flow) creates traps in the bulk of the dielectric. Upon reaching a critical percolation threshold for the trap density, the wave function of trapped charge carriers overlap, which allows charge carriers tunnelling between two adjacent traps. Initially, this process may occur locally, with time eventually forming a path for current flow between the electrodes. As the resistance of one path drops, the charge that is accumulated on the electrode is drained in a short period of time, giving rise to a fast local temperature rise, which in turn accelerates the local failure.

Of course, the rate of trap generation is a function of moving charge, i.e. current. The current is a strong function of the applied electric field. Consequently, at low operating voltages (lower electric field), this accelerated thermal runoff that leads to a catastrophic failure may not exist. The rate of trap generation is significantly slower. Instead, more and more channels for current flow would open with the increase in trap density, leading to a continuous slow drop in resistance. Significant changes only take place at higher electric field. The existence of trapped space charge in the material may alter the field landscape, resulting in local electric field enhancement and local degradation.

It has been proposed [12] that the rate of trap creation at a location x and time t is expressed by:

$$\frac{\partial N_t(x,t)}{\partial t} = J(x,t) l_{scat}^{-1} exp\left[-\frac{E_{a,eff}}{kT}\right] \quad (8)$$

where $N_t(x,t)$ is the trap density (number of traps per unit volume, not the trapped charge density). $J(x,t)$ is the electric current density. l_{scat} is the characteristic distance between subsequent scattering events, and $E_{a,eff}$ is the effective activation energy for trap creation and is comprised of the actual activation energy E_a offset by the energy that an electron acquires from the field $F(x,t)$ while travelling between traps.

To solve the above equation analytically, we need to know the expressions for both current density and electric field which are not possible. An attempt has been made to solve the above equation with some assumptions [12]. It is obvious that the trap generation will be linked to the applied field and duration of the applied field. It has been reported [13] that the trap generation is related to time with a power law, i.e.

$$N_t(t) = k_0 t^{k_1} \quad (9)$$

The higher the applied field, the higher the energy the charges gain. This will lead to that the trap generation in the material increases with the applied field. If we assume that the trap generation is a power function of the applied field, i.e.

$$N_t(E) = k_2 E^{k_3} \quad (10)$$

Combine the two equations we have

$$N_t(E,t) = k t^{k_1} E^{k_3} \quad (11)$$

Our results from LDPE [14 - 15] showed that more traps were generated when the material was subjected to electric field, chemical or thermal ageing.

Now if we assume that there is a critical number of trap N_c beyond it the material would not be able to function, i.e. the end of life, then we can write

$$N_c = N_0 + k t^{k_1} E^{k_3} \quad (12)$$

where N_0 is the trap density of unstressed sample. The above equation can be further simplified:

$$C = N_c - N_0 = k t^{k_1} E^{k_3} \quad (13)$$

The lifetime of the material therefore can be represented as

$$t = C_1 E^{-\frac{k_3}{k_1}} = C_1 E^{-N} \quad (14)$$

where

$$C_1 = \frac{N_c - N_0}{k}$$

and

$$N = \frac{k_3}{k_1}$$

where C_1 is a new constant related to the critical trap density and the material and N is a constant related to the material. Generally, N_c is much greater than N_0.

Equation (20) bears the same form as the empirical inverse power law but with much clearer physical meanings behind. The lifetime of an insulating material now is the time when a critical trap density is reached via trap generation in the material and the ageing process can be described by trap generation. It is important to remember that (20) only applies when the trap generation obeys the power law relationship with time and electric field. It has been reported that the

other forms of insulation lifetime, indicating different a relationship between trap generation and ageing time/electric field. The remaining life of the material can be assessed by measuring the trap density in the material. Therefore, the question now becomes how to estimate trap density in an insulating material!

V. Trap Density Determination and Two Energy Level of Trap Depth Model

Trapping and detrapping are closely related to the trap distribution in terms of spatial and energy in a polymeric material. For a semicrystalline polymeric material, it is possible that traps may have several discrete energy depths or even continuous energy distribution.

Spatially, trap distribution may vary as the material may experience different stresses including physical, thermal, and chemical treatment. This is especially true for the region near to the surface. To simplify the mathematics involved, it is assumed [16] that the traps are uniformly distributed across the sample and only have two trap energy levels, i.e., one representing shallow trap and another for deep trap.

The trapping model can be described by three processes as following: charge injection, trapping, detrapping and kinetics of trapping and detrapping process, respectively. To simplify the model, the trapping process from shallow to deep trap and the detrapping process from deep trap to shallow trap are not considered in the present study. In addition, we assume the trapped charges are close to the injecting electrode, so the recombination with the injected charge from the opposite electrode can be neglected. The details of the model description and how to extract model parameters can be found in [16 - 17].

Based on the above assumption, the kinetics of trapping process can be expressed as follow:

$$\frac{dn_1}{dt} = \frac{J\sigma_1}{q}(N_1 - n_1) - k_1 n_1 \quad (15)$$

$$\frac{dn_2}{dt} = \frac{J\sigma_2}{q}(N_2 - n_2) - k_2 n_2 \quad (16)$$

The emphasis in the model is placed on charge decay after removing the applied field. The detrapping process after the removal of applied field is given below:

$$n_1(t) = n_{10}\exp(-k_1 t) \quad (17)$$

$$n_2(t) = n_{20}\exp(-k_2 t) \quad (18)$$

where n_{10} and n_{20} are the initial trapped charges in shallow and deep trap at the moment when the applied field is removed, respectively.

The total trapped charge density during detrapping process is given by

$$n(t) = n_{10}\exp(-k_1 t) + n_{20}\exp(-k_2 t) \quad (19)$$

where k_1 and k_2 are the thermal detrapping rate constants for shallow and deep traps respectively.

The thermal detrapping rate constant can be expressed as

$$k_{th} = N_c v_{th}\sigma_c \exp\left(-\frac{E_t}{kT}\right) \quad (20)$$

where N_c is the effective density of states in the conduction band, v_{th} is the thermal velocity of the charge, E_t is the trap depth, k is the Boltzmann constant, and T is the temperature.

The parameters k_1, k_2, n_{10}, and n_{20} are important as they are potentially related to microstructure of the material. According to the new ageing model proposed, the changes in parameters will reflect ageing taken place in the material. In details, k_1 and k_2 reflect two different levels of traps in the material which may be related to different kinds of chemical or physical defects in the material. Likeness, n_{10} and n_{20} reflect trap concentration of both shallow and deep traps. The above four parameters can be obtained via data from a series of space charge decay measurements for different stressing times.

Based on the above approach trap density in LDPE and gamma irradiated LDPE was estimated [18] and the results are summarised in Table 1.

Table 1 Trapping parameters extracted from the model fitting

Trap density (m^{-3})	Normal LDPE	Gamma irradiated LDPE
Shallow trap N_1	8.6×10^{18}	3.0×10^{19}
Deep trap N_2	9.3×10^{18}	3.3×10^{19}

The changes in trap density in electrically aged XLPE cable across its radius has also been observed [19] and these changes show a good agreement with physical and chemical variations within the cable. This suggests that the model and its associated trapping parameters are sensitive enough to reflect status of the material.

It is worthy of pointing out that many previous attempts were focused on a single main chemical change to simplify the issue, resulting in certain error. The present approach takes all the changes (both physical and chemical) into consideration, therefore, should be more accurate to predict the lifetime of the material.

VI. Conclusions and Future Work

The paper reviews the existing ageing models and the empirical inverse power law. A simple model based on the injected charge carriers and their impact on the polymeric material has been proposed and the ageing processes in an insulating material can be described in terms of trap generation as the follows:

High electric field (local field enhancement) leads to charge injection into an insulating material and charge accelerate under the influence of the local field to gain kinetic energy. The energetic charge carriers will experience scattering in the material, resulting in energy lose to the

material. This process can lead to bond breaking (in case more 4 eV involved for a polymeric material) and produce physical/chemical changes (scission or oxidation), resulting in the formation of low density region or defects in structure and introducing extra energy levels in terms of energy band theory. Consequently, new traps are created. Once a critical trap density is reached, charge carriers can tunnel the traps, leading to a significant increase in electrical current which will cause further damage to the material and the loss of insulating properties is imminent, i.e. the lifetime of the insulating material.

The model provides not only the physical mechanisms in describing the ageing process but also a new avenue to assess the status of the insulating material. It is possible to estimate trap density in an insulating material based on the two energy levels of trap depth model. By measuring charge profiles using the space charge measurement techniques developed in last three decades and calculating the total amount charge captured and its change with time (decay process), the model allows one to estimate number of traps and its corresponding energy depth by numerical fitting. Initial results demonstrated an increase in trap density after ageing.

Gradual reduction in breakdown strength is the clear sign of material degradation/ageing. It is well known that all degradation/ageing are related to the changes of physical/chemical structures resulting from electrical stressing. Various efforts have been made to establish the relationship between electrical property deterioration and material change. Based on the proposed model, it is possible to relate the reduction in electrical breakdown strength and the trap density created, therefore, the remaining lifetime of the material can be estimated.

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