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Research Proposal

Modeling of Charge Trapping/Detrapping Characteristics in XLPE Cables and Their Relation with Ageing

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1 Introduction

Cable used for high voltage transmission could be generally classified as high voltage dc (HVDC) and high voltage ac (HVAC) cable. The HVAC transmission is vastly preferred way of transferring electric power makes it straightforward to generate electricity and to transform voltages up and down. But in many cases, the HVDC will be chosen behind numerous reasons. The arguments of the favouring on dc technology could be summarized as low energy loss, low cost on transmission cable, and asynchronous connections. However, during long-term operation for both type of HV cables, ageing process will cause raise of amorphous region ratio, create more microvoids and discontinuities, chain scission, oxidation and hydrolysis [1]. These will introduces more physical and chemical defects into the materials [2] and lead to rise of localized states residing within the wide band gap. And those localized states, or namely 'traps', with density N, offer charge carriers an intermediate state at certain energy level, which is defined as the 'trap depth', E_t. Also, the ability of these traps to capture charge carriers relates to the trapping cross-section area S. Here, under the assumption of Coulombic attractive trap [3], and one trap could only accommodate one charge carrier, we take the cross-section area as $S = \pi r^2$, where r is distance between the trap and its charge carrier. Above all, trap density N, trap depth E_t, and trapping cross-section area S are generally called trapping parameters. They depict the attributes of traps. In our research, we aim to take advantage of these attributes of 'traps' to monitor ageing for different-degree aged insulation materials.

2 Motivation and State of the Art

In [4], space charge has been treated as both cause and consequence of ageing. In the present research, we aim to simulate of space charge trapping-detrapping behaviour in polymer by using a improved model and further utilize trapping parameters estimated from the model for each type of aged materials to reflect the degree of ageing quantitatively.

Early in 1994, by applying finite element method to the specimen film, the bipolar transport model was initially proposed by Allison and Hill for simulation of charge profiles in degassed XLPE materials [5]. In the model, electrons and holes will inject from two electrodes. Subjected to external electric stressing, injected electrons and holes will move towards the opposite electrodes. During migration process, mobile charges might be captured by traps in the materials and recombination might be occur between mobile/trapped electrons and holes. And when mobile electrons/holes travel near opposite electrodes, those charges will escape from the sample bulk. In [5], both electrodes were pre-stressed in a period and there are extraction barrier for charge outflow. For the charge conduction process, effective constant mobility was applied. In the same year, Fukuma et al. modified on the model that considering injection barrier (Schottky injection) and extraction barrier at both electrodes. Meanwhile, the hopping conduction mechanism was utilized to calculate the mobility as field-dependent. Thereafter in works done by Roy (2004) [6], the model was developed in order to reproduce qualitatively the experimental behaviour reported for polyethylene materials including external current density, electroluminescence (EL) and charge profiles when using different protocols of voltage application: a constant field, a step increased voltage and a polingdepoling scheme. However, in bipolar transport model, definitions of some parameters need more verifications. For trapping coefficients used in the model, is set to be as a constant, which should be a function of charge drift velocity in materials and trapping cross section area [1]. Moreover, detrapping process is also ignored in such model.

In [7], for the case of epoxy resin, Dissado (2006) et al [7] proposed a model considering detrapping process within three steps. The traps' depth is assumed to be in a range from $E_{t_{min}}$ to $E_{t_{max}}$. And $t_1 = [\nu_0 \exp(-E_{t_{min}}/kT)]^{-1}$ is the time for all trapped charges escaping from shallower depths (below $E_{t_{min}}$) and meanwhile charges at deeper trap depth could start to detrap from trap sites deeper than $E_{t_{min}}$, and then $t_2 = [\nu_0 \exp(-E_{t_{max}}/kT)]^{-1}$ is the time for charges being emptied at all deeper trap sites. When $t > t_2$, the value of $Q(t)$ reduces gradually to zero as the deepest filled trap states has escaped. And in 2012, Tzimas et al. [8] applied this model on 2 and 26 hours pre-stressed samples and further grouped the total traps into two ranges, shallow and deep traps. The minimum ($E_{t_{min}}$) and maximum limits ($E_{t_{max}}$) of both shallow and deep traps' ranges could be found through locating the t_1 and t_2 fit within experimental data.

The fitting parameters of trap depth ranges and densities shown that the most of negative trapped charges is close to the cathode are captured in shallow states after 2 hours but is partly transferred to deep traps after 26 hours stressing, consequently a longer decay time. In [9], Chen proposed a trapping-detrapping model based on two energy levels. Thereafter in [10], by applying the model from [9] fitting with experimental data from depolarization testss, trapping parameters of low-density polyethylene (LDPE) and gamma-irradiated LDPE were estimated. The comparison between results of these two materials indicated that the physical and chemical changes brought by the irradiation process alter the trapping parameters, especially for trap density and deep trap depth. The basic ideas of two approaches proposed in [7] are quite similar:

- Both numerical models are applied to condition of charge relaxation after the removal of an external voltage and the trapping parameters are obtained by fitting curves of specific model parameters with experimental data from depolarization tests.
- Observed charge dynamics during volts-off condition was considered as the decay of trapped charges, i.e. mobile charges generated the detrapping process were assumed escaping from the sample instantly, and only detrapping process was taken into consideration.
- Both models treat traps with a range of energy levels as traps at two equivalent levels: shallow traps and deep traps. These two types of traps probably relate to physical (shallow) and chemical defects (deep) respectively [2].

3 Present Modelling Work

As mentioned above, models established in [7] and [9] only simulate the charge dynamics in depolarization process and ignore the retrapping process after the removal of external voltage. In present research, we have developed two models improved from [9]. The improvements could be summarized as:

- The model in [9] ignore the energy barrier lowering caused by local electric field. For the two improved models, the energy barrier lowering term of both models were based on the corrected three-dimensional Poole-Frenkel mechanism [11].
- For values of trapping cross-sectional area in [9], they are estimated directly from curve fitting process. In present improved models, the trapping cross-sectional area was proposed to be a function of averaged electric field [12] and trap depth [13].
- As mentioned, the model in [9] does not take account of charge retrapping process after removal of external voltage. Both models take charge retrapping process into consideration and the first improved model finally give a analytic solution in form of hyperbolic cotangent function to depict the charge dynamics during volts-off period.
- Furthermore, for the second improved model, the charge accumulation process during pre-stressing period was considered for estimation of trapping parameters. And injected charges from electrodes were suggested conforming to Schottky mechanism.
- For the sake of simplicity, in the first improved model, some field-dependent parameters including energy barrier lowering and trapping cross-sectional area were treated as constants for each type of sample. In the second improved model, these parameters were made varying with mean field across the sample. Hence, the second improved model could better describe the charge trapping-detrapping process but could not give analytic solutions. Instead, numerical solutions could be found for the second model, but it is time-consuming to find optimum curve fitting with the same experimental data.

4 Sample Preparation

In our project, small sections of XLPE cables were taken from high voltage ac service conditions of 220kV operated for $8, 12$ years and of 110kV for $2, 11$ years respectively. Moreover, during a long-term operation condition, XLPE cables at different locations have to endure different electric field stresses. Consequently, the trapping parameters may be position dependent. In order to study differences on trapping parameter samples of different ageing years and also the effect of location on charge dynamics, the XLPE of cable insulator will be sliced to films by a rotary skiver (a cutting machine to make film by rotation) from the surface of cable insulator. The thickness of obtained samples should be 100-200 μm with smooth surfaces. For the removal of volatile chemicals in the films, the cut films must be treated in vacuum oven at 80°C for 48 hours for degassing [8][14].

The film samples for all the experiments were classified to several parts according to the distance from the surface of cable insulator. In present research, three different positions were selected as the outer (0-5 mm from surface), middle (14-18 mm), and inner (23-31 mm) layer for 12-year-operated cable and the outer (0-5 mm from surface), middle (10-15 mm), and inner (20-27 mm) layer for 8-year-operated cable.

5 Experimental Design

The pulsed electroacoustic (PEA) technique will be used for observing dynamics of charge profiles and measurements were designed for 30 minutes after the removal of the applied voltage. For XLPE films with different thickness (samples with thicker thicknesses 120-180 μm selected), the protocol of applied voltage should be adjusted so the applied field could be fixed at 40 kV/mm for all the samples. The time of the applied voltage was set to be 6 minutes.

Moreover, the oxidation products produced in XLPE insulator could be analyzed by Fourier Transform Infra-Red (FTIR) spectroscopy. The spectrum could be observed by the IR absorption in the range 4004000 cm^{-1} through XLPE film using a Shimadzu "IR Prestige-21" spectrometer. The spectrum would be gathered by 20 scans accumulation, and the resolution is 4 cm^{-1}. Before the experiment, samples would be cleaned by alcohol and then dried. To reduce the impacts on the test results yielded by alcohol cleaning, samples should be kept for half an hour at room temperature after drying.

For the same type XLPE of samples with thinner thicknesses (100$\pm$10 μm selected), the dc breakdown tests were expected to be carried out. As was done with thicker samples for PEA test, those samples should also be processed with degassing treatment. For these experiments, the prepared samples must be tightly fixed between two sphere electrodes with diameter of 6.5mm tightly. The external voltage could be applied as ramping voltage stepping with 100 V/s from zero. Moreover, in order to avoid flashover during test, the two spherical electrodes with the tested sample in between must be immersed in insulating oil. For each type of sample, 20 measurements were expected to be made in order to to reduce statistical error.

6 Expected Results

By fitting with experimental data, trapping parameters could be obtained by using both improved models. Several results are expected as below:

- By comparison with data from dc breakdown test, it is extrapolated that trapping parameters should correspond with breakdown strengths of different type of XLPE materials. For example, with increase of trap density, breakdown strength will decline. In other words, it is expected that the trapping parameters estimated from both models could be used as ageing markers to distinguish different degree-aged materials.

- Furthermore, a relationship between trapping parameters and insulation lifetime is supposed to be proposed. We finally expect that by applying our approach on certain insulation material, its degree of ageing could be quantized and insulation lifetime of such material could be estimated.

References

[1] L. Dissado and J. Fothergill, *Electrical degradation and breakdown in polymers*, 9th ed., P. N. Morgan, D.V. and K. Overshott, Eds. Peters Peregrinus Ltd., London, United Kingdom, 1992.

[2] D. Marsacq, P. Hourquebie, L. Olmedo, and H. Janah, "Effects of physical and chemical defects of polyethylene on space charge behaviour," in *Electrical Insulation and Dielectric Phenomena, 1995. Annual Report., Conference on*, 123, 1995, pp. 672–675.

[3] K. C. Kao, "Dielectric phenomena in solids with emphasis with physical concepts of electronic processes." Manitoba: British Library Cataloguing in Publication Data, 2004, ch. Charge carrier injection through potential barriers from contacts, pp. 345–347.

[4] G. Mazzanti, G. Montanari, and L. Dissado, "Electrical aging and life models: the role of space charge," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 12, no. 5, pp. 876–890, 2005.

[5] J. Alison and R. Hill, "A model for bipolar charge transport, trapping and recombination in degassed crosslinked polyethene," *Journal of Physics D: Applied Physics*, vol. 27, no. 6, pp. 1291–1299, 1994.

[6] S. Roy, P. Segur, G. Teyssedre, and C. Laurent, "Description of bipolar charge transport in polyethylene using a fluid model with a constant mobility: model prediction," *Journal of Physics D: Applied Physics*, vol. 37, no. 2, pp. 298–305, 2004.

[7] L. Dissado, V. Griseri, W. Peasgood, E. Cooper, K. Fukunaga, and J. Fothergill, "Decay of space charge in a glassy epoxy resin following voltage removal," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 13, no. 4, pp. 903–916, 2006.

[8] A. Tzimas, S. Rowland, and L. Dissado, "Effect of electrical and thermal stressing on charge traps in XLPE cable insulation," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 6, pp. 2145–2154, 2012.

[9] G. Chen and Z. Xu, "Charge trapping and detrapping in polymeric materials," *Journal of Applied Physics*, vol. 106, no. 12, p. 123707, 2009.

[10] T. Zhou, G. Chen, R. Liao, and Z. Xu, "Charge trapping and detrapping in polymeric materials: Trapping parameters," *Journal of Applied Physics*, vol. 110, no. 4, p. 043724, 2011.

[11] M. Ieda, G. Sawa, and S. Kato, "A Consideration of Poole-Frenkel Effect on Electric Conduction in Insulators," *Journal of Applied Physics*, vol. 42, no. 10, pp. 3737–3740, 1971.

[12] D. Buchanan, M. Fischetti, and D. DiMaria, "Coulombic and neutral trapping centers in silicon dioxide," *Phys. Rev. B*, vol. 43, pp. 1471–1486.

[13] G. Blaise and W. Sarjeant, "Space charge in dielectrics. energy storage and transfer dynamics from atomistic to macroscopic scale," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 5, pp. 779–808, 1998.

[14] K. Suh, S. Hwang, J. Noh, and T. Takada, "Effects of constituents of xlpe on the formation of space charge," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 1, no. 6, pp. 1077–1083, 1994.