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Influence of Endurance tests on Space Charge Distribution of 160kV HVDC XLPE Cable

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Abstract – The ageing of XLPE cable insulation will lead to the accelerating accumulation of space charge, which will greatly affect the safe operation of the HVDC cable. In order to investigate the influence of different ageing modes on the space charge distribution of the HVDC cable, thermal stressed, electrical stressed and electro-thermal stressed endurance tests were carried out on the XLPE peelings. The tested XLPE peelings were obtained from 160kV HVDC cable insulation. The endurance tests were carried at thermal stress of 363K, electrical stress of 20kV/mm DC and a combination of both. The Pulsed Electro-Acoustic (PEA) method was used to measure the space charge distribution of the samples. The influences of ageing on the trap energy distribution were analyzed based on the isothermal relaxation theory and the decay characteristics of the space charge. The results showed that thermal ageing would help to improve the crystalline morphologies of the XLPE at the early stage. The total amount of space charge decreased compared to the ones before thermal ageing. The long term of electrical stress would result in the cleavage of polymer molecule chains which would intensify the accumulation of space charge and increase the density and depth of electron traps. With a combination of electrical and thermal stress, the injection and migration of space charge were more significant. Besides, the depth and density of electron traps increased rapidly with the increase of endurance time.

Keywords: Endurance test, HVDC cable, XLPE, Space charge, Trap energy

1. Introduction

The development and utilization of green renewable energy is becoming increasingly important due to the shortage of traditional energy and degradation of environment. Flexible HVDC technology has provided a solution for large scale of renewable energy integration. Since the flexible HVDC doesn't involve the polarity inversion problem, the extruded XLPE cable has made rapid progress in recent years [1, 2]. Several HVDC XLPE cables have been in service for decades in the worldwide [3, 4].

Space charge in the XLPE insulation has been an emergency problem and has limited the development of HVDC cable. The formation, migration and accumulation of space charge will lead to localized electric stress enhancement in the bulk of insulation which will result in the electrical ageing or even breakdown of the HVDC cable [5-7]. In order to investigate the influence of ageing on the space charge distribution in XLPE cable, a series of studies have been conducted in recent years. Space charge characteristics of cross-linked polyethylene aged by thermal stress or electric stress were analyzed in [8, 9]. Antonio Tzimas studied the effect of electrical and thermal stress on charge traps in XLPE cable insulation [10]. Pyrolysis activation energy and molecular structure of different thermal ageing stage were analyzed in [11, 12] which made a conclusion that low temperature thermal stress (below 100℃) would make an improvement of the XLPE crystalline morphologies. However, a long-term thermal ageing or high temperature thermal stress will greatly deteriorate the XLPE material. Average charge density, total space charge, apparent charge mobility and trap energy distribution were the characteristic parameters of space charge which could be used for the evaluation of aging state [13-16].

In this paper, samples from a 160kV HVDC cable were accelerated aged under electrical stress, thermal stress and electro-thermal stress. Pulsed Electro-Acoustic (PEA) method was used for the measurement of space charge distribution. Average space charge density and electron trap energy were calculated as the characteristic parameters of space charge. At last, the influences of different kinds of endurance stresses on the space charge distributions were compared and analyzed.

2. Experimental Setup

2.1 Sample preparation

The materials used for the ageing tests were slices from a160kV HVDC cable which has been in service in Nan'ao

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Island. The slices were cut into 45*45*0.5mm in size. Before all ageing tests, the samples were put into a vacuum oven at 343K for 24 hours in order to eliminate the influence of mechanical stress caused by slicer.

2.2 Endurance test

The insulation materials for the endurance tests were produced by BOREAILS with 20kV/mm max operation field strength and 343K maximum operation temperature.

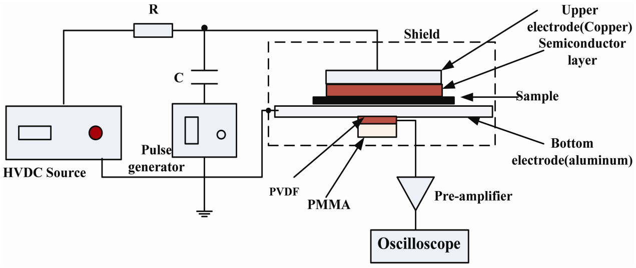
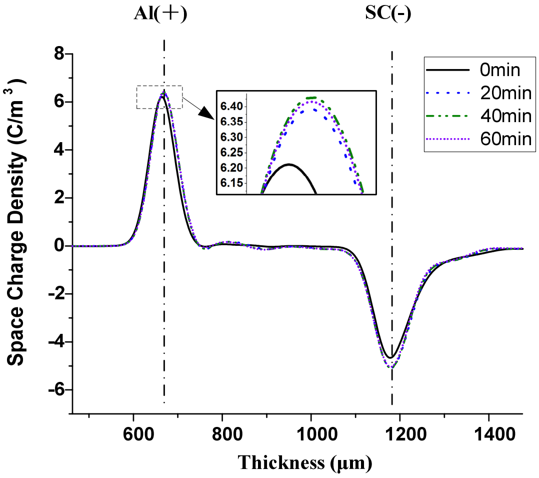
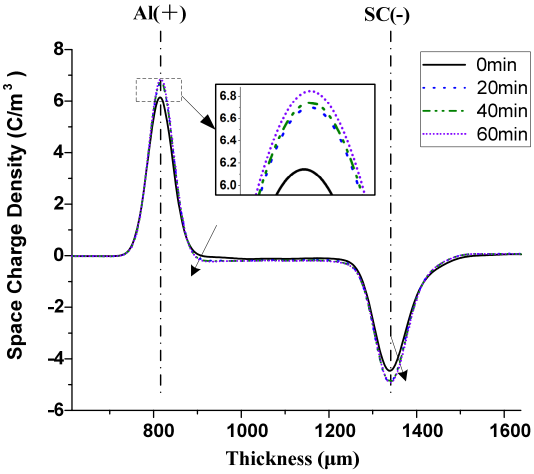


Fig. 1. PEA space charge measurement device

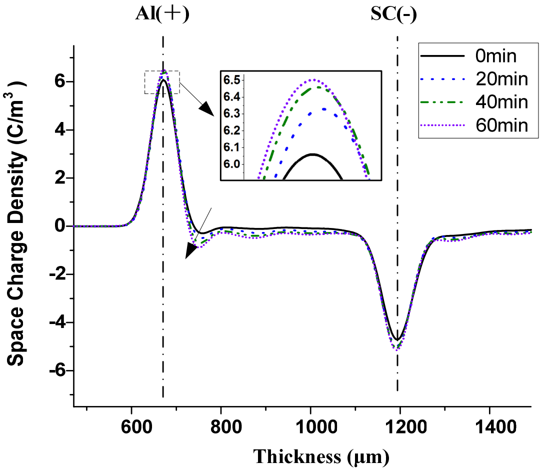
The samples were stressed under the following condition, a) thermal stress of 363K for 70 days (marked as T70d); b) electrical stress of 20kV/mm DC for 70 days (E70d); c) electro-thermal stress of 20kV/mm DC at 363K for 50 and 60 days (ET50d and ET60d).



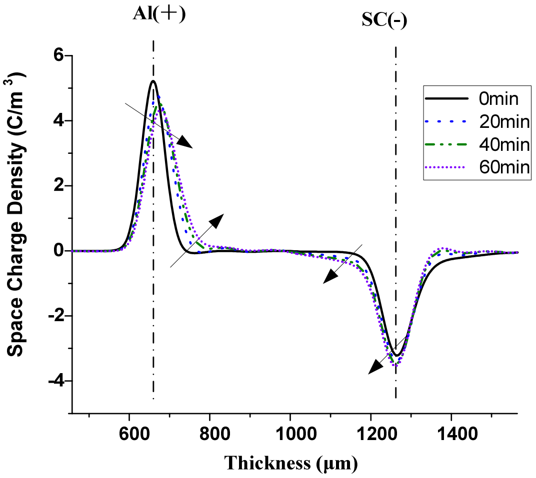
(a) Un-aged sample



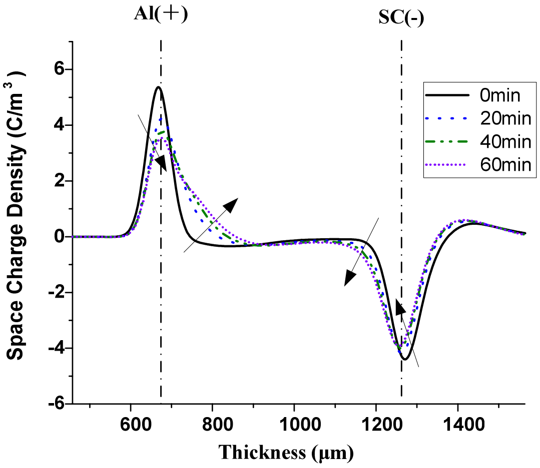
(b) Thermal stressed sample(70d)



(c) Electrical stressed sample(70d)



(d) Electro-thermal stressed sample(50d)



(e) Electro-thermal stressed sample(60d)

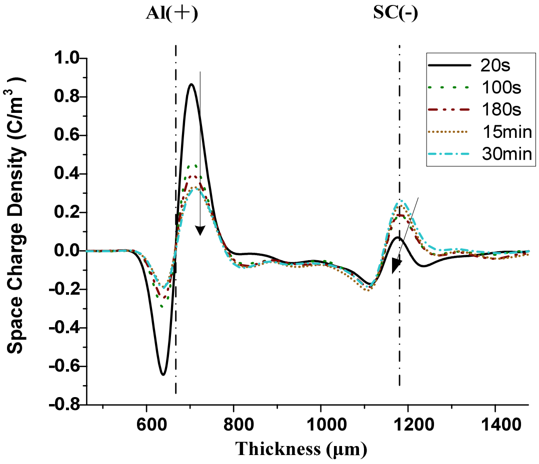
Fig. 2. Space charge distribution of different stressed samples with voltage on

After the ageing tests, all the samples were thoroughly cleared by anhydrous alcohol in order to remove the surface stains, and then the samples were dried in oven for 8 hours.

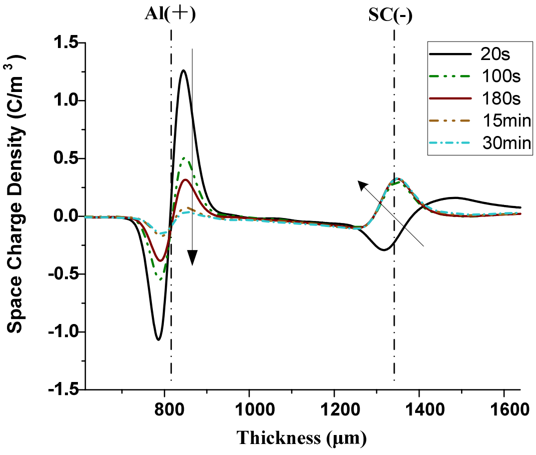
2.3 PEA measurement

Pulsed Electro-Acoustic (PEA) method was used for the measurement of the space charge distribution. The measurement apparatus is shown in Fig. 1. The materials of the upper and bottom electrodes are copper and aluminum, respectively. The acoustic signal generated by the force on the charge is detected by a piezoelectric PVDF film attached to the bottom electrode. Besides, a polymethyl methacrylate (PMMA) film adjacent to the PVDF film is used for the absorber layer in order to prevent acoustic reflection. At each interface, a thin layer of silicon oil was applied to avoid any air gaps for a better acoustic transmission.

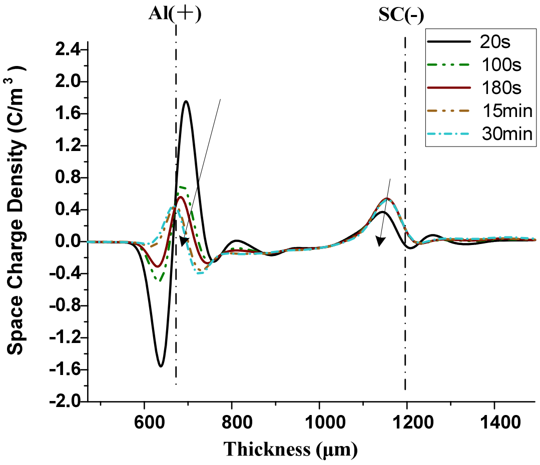
The voltage on space charge distribution characteristics were measured at 20kV/mm. And the data of space charge at 0min, 10min, 20min, 30min, 40min, 50min and 60min were measured respectively with the voltage on. Then the sample was short circuited for 30min during which the space charge de-trapping characteristics were measured. In order to increase the accuracy of test results, the average of



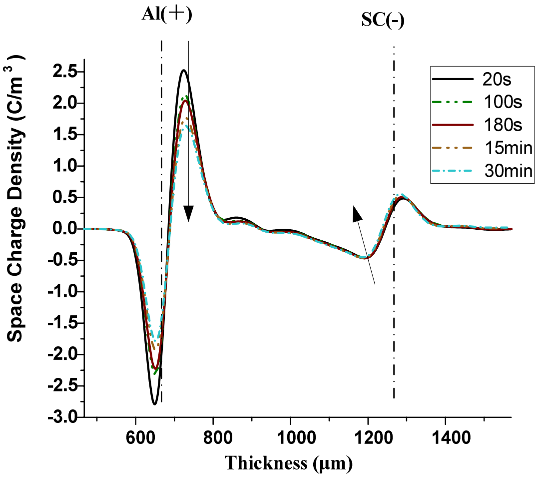
(a) Un-aged sample



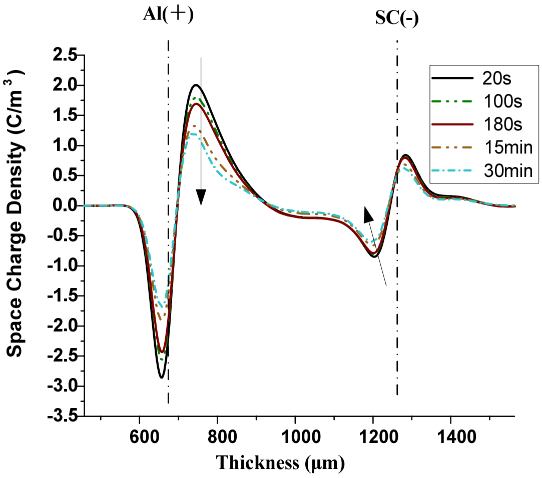
(b) Thermal stressed sample(70d)



(c) Electrical stressed sample(70d)



(d) Electro-thermal stressed sample(50d)



(e) Electro-thermal stressed sample(60d)

Fig. 3. Space charge distribution of different stressed samples with voltage off

1000 sets of measured data were calculated.

3. Experimental results

3.1 Space charge distribution with voltage on

Fig. 2 shows the space charge distribution of samples under different stresses. As can be seen from the figure, except for electro-thermal stressed samples, charge injection and accumulation phenomenon were not obvious at most of the samples. As for the electro-thermal stressed samples, the space charge injection was more obvious than other samples. Besides, there was mainly positive charge injected into the sample. What is more, the space charge migrated to the inner of the sample slightly with time. Compared the figures of ET50d and ET60d, the injection and migration phenomenon became much more serious for a longer endurance time which indicated that electro-thermal stress could cause a more serious damage to the XLPE peelings with a more rapid rate than other kind of stresses.

3.2 Space charge decay characteristic with voltage off

Space charge decay tests were carried on each sample right after the voltage on tests with the applied voltage off for 30 minutes. The results are shown in Fig. 3. As can be seen from the results, opposite charges were induced at the interface of the sample and electrode. The maximum space charge occurred at the anode and the induced space charge density at the cathode was relatively small (less than 0.5C/m^3). The positive and negative charges dissipated rapidly at the first 200 seconds and then the dissipation rate slowed down. Most of the space charge could decay to saturation in 15 minutes. As for the E70d and T70d samples, the space charge at the anode almost dissipated completely to a level less than 0.05C/m^3 which could be negligible. However the space charge at the cathode dissipated at a relative slow rate and there was still a density of 0.2C/m^3 space charge could not be released at the end of test time (30 minutes). Compared the samples before and after the endurance tests, the initial space charge density of the electro-thermal stressed samples was much larger than those of other stressed samples and was about 3 times of the fresh one. Besides, the dissipation rate was much slower than other samples and the induced space charge density at the anode were both larger than 1C/m^3 after 30 minutes which was much larger than the others.

4. Discussions

In order for a more precisely analysis of the influences of different stress endurances on the space charge distribution characteristics of the HVDC cable insulation material, the relevant characteristic parameters were calculated and analyzed in this paper. The parameters contain space charge polarity, average space charge density and space charge trap energy distribution.

4.1 Space charge polarities of the samples under different stress endurances

As can be seen from the above results, it is obvious that the samples under different stress endurance tests possess different space charge distribution and decay characteristics. In particular, the polarity of the samples after different stress endurance tests can be regarded as an indication of the ageing marker. As discussed in [14], the polarity of space charge next to the electrodes depended on the residuals, degradations and so on. When the samples are seriously aged, residues or other by-products are produced which will result in the present of heterocharge. On the contrary, homocharge or no charge will form when there are no residues or the samples are not yet seriously aged.

From the space charge distribution and decay characteristics at 20kV/mm, little charge was formed except for the electro-thermal stressed samples. As for the electro-thermal stressed sample, there was a certain amount of homocharge formed in the surface of the sample and the injected space charge seemed to migrate toward the inner of the insulation. No obvious heterocharge was found in all the stressed samples which indicated that the samples were not serious deteriorated and the ageing-resistant performance and space charge suppression ability of the tested material were relatively good which provided a guarantee for the safe operation of the HVDC cable.

However, it must be pointed out that, though there is no heterocharge observed in the tests, the total space charge amount increases significantly compared to the fresh one. Some longer time of endurance tests are needed to carry on for the sake of exploring the long term operation performance of the cable.

4.2 Average space charge density

Average space charge density is related to the electrical, physical and microcosmic characteristics of the samples. The average space charge density can be calculated based on the space charge distribution according to the following Eq. (1),

$$q(t) = \frac{1}{d}\int_0^d \left|\rho(x,t)\right| dx \tag{1}$$

where d is the thickness of the test sample, m. $\rho(x, t)$ is the space charge density (C/m^3) at position x (m)and time t (s).

As stated in [17], average space charge densities of the voltage off test can reflect the generating and distribution of the traps and may be a quantitative method to assess the degree of ageing. So the decay characteristics were mainly discussed in this paper. The average space charge densities of different stressed samples with voltage off are shown in Fig. 4.

As shown in Fig. 4, most of the decay characteristics of the average space charge density (or total space charge amount) fit the exponential decay model with a relatively rapid decay rate at the early stage and then slowed down with time. The average space charge density in electrical stressed or thermal stressed samples had a relatively small difference with the fresh one. The space charge density of E70d increased slightly compared to the fresh one which could be explained by the degradation of polyethylene molecular caused by long term of high electrical stress. In contrast, the space charge density of T70d decreased compared to that of un-aged. During the thermal endurance test, post-crosslinking might occurr simultaneously with the degradation of the XLPE, and the post-crosslinking could optimize the crystalline morphologies of the insulation, which would reduce the accumulation of the space charge. Similar results were also obtained in [11, 18-20]. However, it is important to point out that the thermal degradation will dominate the process when the thermal endurance time is longer or the temperature is higher. And the long term thermal degradation will result in the cleavage of XLPE molecular chains, producing more low molecular weight byproducts which are known for the cause of space charge accumulation [14].

Compare to E70d and T70d, the electro-thermal stressed samples have a much larger density (from 0.15 C/m^3 to 0.4C/m^3) which indicates that there are more traps formed in the electro-thermal stressed samples and more charge formed in the bulk of the insulation. The phenomenon can be explained as followed. In the electro-thermal stress endurance test, more traps will be injected and trapped with the electrical and thermal stresses combined. What's more, the elevated temperature (up to 90℃) can promote the injection of the space charge which leads to the increase of the average density[21]. Besides, the electrons and material molecules are more active at an elevated temperature which will benefit the charge reaching the deeper traps. With more space charge accumulated, the localized electrical field stress will be further enhanced which in turn can cause the further deterioration of the insulation. Therefore, it should avoid overload or overvoltage in the operation of HVDC to eliminate the injection and accumulation of space charge in the bulk of the insulation.

4.3 Space charge decay characteristics

Table 1. Parameters of average space charge density decay model

	τ_1	τ_2	τ_3	R
T70	2.34627	40.76301	40.76476	0.99713
E70	8.25584	51.11569	227.3388	0.99869
ET50	2.74102	48.72968	1016.038	0.99946
ET60	353.2838	12751.29	12994.25	0.99919
Un-aged	41.24028	41.24747	1124.879	0.94731

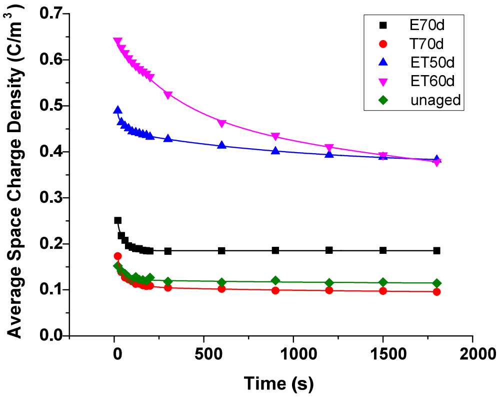


Fig. 4. Average charge density at voltage off

As shown in Fig. 4, most of the decay characteristic of the average space charge density fit a third-order exponential decay model (Eq. 2) rather than one-order exponential decay model expressed in [16].

$$\sigma(t) = \sigma_0 + \sum_{i=1}^{3} A_i e^{-\frac{t}{\tau_i}} \tag{2}$$

where, σ(t) is the space charge density as a function of time t . σ_0 represents the residual charge density which can be an indication of the density of deep traps in the bulk of insulation. A_i is the coefficient of each section. τ_i is the time constant for each item.

In this paper, LM (Levenberg-Marquardt Method) method is adopted for the curve fitting of Fig. 4. The results are shown in Fig. 4 (solid line) and Table 1.

4.4 Trap energy distribution

According to the isothermal relaxation theory, electron will escape from the traps when be excited. The de-trapped electrons will form a current $I(t)$ in the external circuit which can be expressed as followed[22],

$$I(t) = \frac{qLkT}{2t} f_0(E_t) N(E_t) \tag{3}$$

where, q is the electron charge, 1.6×10^{-19}C. t is the decay time, s. L is the thickness of the sample, m. k is the Boltzmann's constant, 8.568×10^{-5}eV/K. T is the absolute temperature, K. $f_0(E_t)$ is the initial occupation rate of traps inside the dielectrics. $N_t(E_t)$ is the trap energy density at trap level E_t (eV).

The relationship of trap level E_t and time t is shown in Eq. (4).

$$E_t = kT\ln(vt) \tag{4}$$

where, v is the frequency of electron vibration, and as for polyethylene material, $v=3\times10^{12}S^{-1}$.

The de-trapping process of the space charge in PEA tests are similar to that in IRC tests. When space charges are injected into the sample, some of them are captured by the traps in the bulk of the sample. When the voltage is off, the ones captured by the shallow traps escape easier and earlier. In contrast, the ones captured by the deep traps will need more time and energy to escape from the traps. Supposing that the released electron will not be trapped again in the decay process[23, 24]. As can be seen in Fig. 2, most of the space charge were induced on the surface of the specimens. Then, the $N_t(E_t)$ is independent of the position x, and Eq. (2) can be appropriate seen as the attenuation characteristic of the space charge in the traps. The space charge decay current can reflect the distribution of the trap energy in the bulk of the sample.

An appropriate isothermal relaxation current can be derived from Eq. (2).

$$\left|I(t)\right| \approx \left|\frac{d\sigma(t)}{dt}\right| = \sum_{i=1}^{3}\frac{A_i}{\tau_i}e^{-\frac{t}{\tau_i}} \tag{5}$$

As can be seen from Eq. (3), the density of trap energy $N_t(E_t)$ is proportional to $I(t)\cdot t$ ($N(E_t)\propto I(t)*t$)which can represent the density distribution of the trap energy, $(\text{eV})^{-1}$.

The isothermal relaxation current of XLPE cable is typically composed of three items, namely the interfacial polarization of inner semiconductor and XLPE insulation, interfacial polarization of crystal area and amorphous area and the polarization of interfaces among salt hydrates produced by XLPE ageing. The constants of the three polarization items are τ_1, τ_2 and τ_3 ($\tau_1<\tau_2<\tau_3$), respectively. The isothermal relaxation current can be expressed as a third-order exponential decay model which is similar to Eq. (2) and (5). Therefore, Eq. (5) which is derived from Eq. (2) can be seen as the appropriate isothermal current in the PEA test.

The polarization time constants of the space charge decay data are shown in Table 1. As for τ_1, it will be influenced by the interface between the electrode and the sample which may introduce errors in the assessing of trap energy distribution. As for τ_3 which is mainly influenced by the ageing state, it will reflect the impact of ageing on the specimen more properly. So, the trap density mainly based on the τ_3 term was chosen for the evaluation of the trap density changes caused by endurance tests, which can be expressed as $N'(E_t)$, $(\text{eV})^{-1}$.

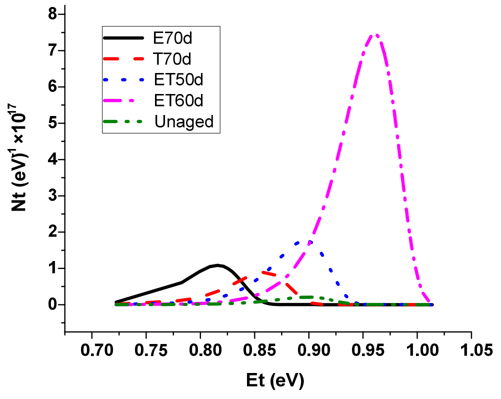


Fig. 5. Trap energy distribution of different stressed samples

For $I_3(t)\approx A_3/\tau_3\cdot\exp(-t/\tau_3)$, then $I_3(t)\cdot t \propto N'(E_t)$. As for the aim of evaluation, $N'(E_t)$ can be calculated as Eq. (6) for simplify.

$$N'(E_t) = I_3(t)\cdot t = \frac{A_3}{\tau_3}e^{-\frac{t}{\tau_3}}\cdot t \tag{6}$$

Combined Eq. (4) and (6), the trap energy density $N'(E_t)$ distribution of different stressed samples can be calculated, the results are shown in the Fig. 5.

Fig. 5 shows that the trap energy of the tested XLPE samples range from 0.7 to 1.02 eV which can be seen as shallow traps (E_t<1.10eV shallow trap and E_t>1.10eV deep trap). Compared the trap energy distribution of different stressed samples, the one under electro-thermal stress had larger density and deeper traps which indicated that there would be more space charge injected into the bulk of sample and the decay rate would be more slowly with deeper traps. As for the thermal stressed samples, the trap density was smaller than the electrical stressed ones indicating that there were fewer traps than the electrical stressed samples.

5. Conclusion

Insulation peelings from a 160kV HVDC cable were stressed under thermal stress, electrical stress and electro-thermal stress in this paper. The space charge distribution characteristics and the trap energy distribution were analyzed based on the PEA measurement results. The conclusions are as follows.

The materials used for the ageing tests were slices of a 160kV HVDC which has been in service in Nan'ao Island. The PEA results showed that tthe space charge injection and accumulation phenomenon were not obvious in all the samples expect for the electro-thermal stressed one. What's more, there was no hetero space charge found in all the samples. The results indicates that the ageing-resistant performance and space charge suppression ability of the tested HVDC cable insulation are relatively good which provides a guarantee for the safe operation of the HVDC cable.

The decay characteristics of the average space charge density (or the total space charge) fit the third-order exponential decay model which can be used for the derivation of approximately isothermal relaxation current model. And then the trap energy distribution can be calculated.

The injection and accumulation phenomenon in the electro-thermal samples were more obvious than those in other samples. The space charge density, trap depth and the total amount of the traps were significantly increased compared to the un-aged samples. The space charge density increased with the increase of the trap amount. And it would be more difficult for the de-trapping process when the trap depth increased. The electro-thermal stress had the greatest influence on the XLPE insulation and would cause the increase of space charge density in the bulk of the insulation. Therefore it is wisdom to avoid overload in the practical operation of the HVDC cable in order to restrict the accelerated ageing of the insulation.

Post-crosslinking in the early stage of the thermal stress test might occur and optimized the crystalline morphologies of the XLPE insulation. As for a longer term of thermal stress, the electron density and depth will both increase with time. The initial space charge density of the decay test is proportional to the trap density. And the de-trapping rate is mainly influenced by the trap depth.

Electrical stress will cause the cleavage of the polyethylene molecular chain which will produce more low molecular weight byproducts, resulting in an increase of the space charge density of the insulation.

Acknowledgements

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