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A Study on the Space Charge Characteristics of AC Sliced XLPE Cables

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ABSTRACT Cross-linked polyethylene (XLPE) cables are widely used in power systems due to their excellent electrical and mechanical properties. Space charge is an important factor in cable aging and breakdown. At present, XLPE cables in the power system are mainly ac XLPE cables, so it is necessary to study the space charge characteristics under ac voltage. In this paper, an electro-thermal aging platform for XLPE cable was built and a 10-kV cable was aged. XLPE slices were obtained from the aging cable and ac space charge experiments were carried out on the XLPE slices at different stages of aging. The trap energy levels were calculated and the effects of different electric fields on the ac space charge characteristics were compared. The experimental results show that the trap energy level increases with the aging process and the non-averaged electric field is a necessary condition for charge migration.

INDEX TERMS Space charge, XLPE cable, electro-thermal aging, trap level, ac experiment.

I. INTRODUCTION

Cross-linked polyethylene (XLPE) AC power cables are widely used in power systems and their reliability is closely related to the stable operation of the power system. Space charge is an important cause of insulation degradation of the cables [1]–[3]. During the operation of the cable, space charges accumulate inside the XLPE insulation and the local electric field is seriously distorted due to continuous high voltage and aging. The trapping, de-trapping, and recombination of the charges at the defect are accompanied by the release and transfer of energy, which destroy the main insulation of the XLPE [4]–[6]. The tests and analysis of the dynamic characteristics of the space charge in the AC cable insulation is of great significance for the study of cable aging mechanism.

Over the past 30 years, the pulsed electro-acoustic (PEA) method and space charge characteristics of polyethylene (PE) materials have been studied extensively. However, these studies have mainly focused on the space charge characteristics under DC electric fields [7]–[10]. Test objects have included PE and XLPE sheet materials and cable bodies [11], [12]. As testing space charge under AC voltage has high requirements for hardware devices, fewer studies have been conducted in this area of research. However, investigators have verified the role of space charge under alternating electric fields through experimental data. Therefore, it is necessary to study the space charge of cable insulation under AC electric fields.

In this paper, the AC space charge characteristics of cable insulation were studied. Also accelerated aging of a 10 kV XLPE cable was performed and the AC space charge at different aging stages was determined. The trap energy level was calculated to obtain the curve of the trap energy level with aging time. A long-term AC polarization experiment was performed on the sliced cable after aging to observe difference in the AC space charge under uniform and non-uniform electric fields. The experimental results show that the trap energy level increases with the aging process and the non-averaged electric field is a necessary condition for charge migration.

II. THE TEST METHOD

A. THE PEA METHOD PLATFORM UNDER AC CONDITION

Space charge profiles were measured through the space charge measurement system for laminated samples under ac stress, whose structural diagram is shown in Figure 1. The principle of the measurement system is based on pulsed electro-acoustic method, and the sample is submitted to

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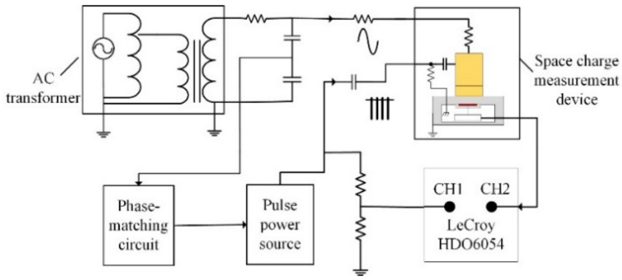


FIGURE 1. **Space charge measurement system for laminated sample under ac conditions.**

pulsed electric field generated by high-voltage pulse power supply, which generates electrostatic forces on existing charges. Thus, ultrasonic waves are induced and transformed into electric signals by a piezoelectric sensor, which reflects the distribution of space charge in the sample.

For charge measurement under ac stress, the difficulty is the match of measurement time with ac phases compared with charge measurement under ac stress. In addition, acoustic signals need to be recorded over several periods to be averaged afterwards. In previous works, either trains of pulses were produced at desired positions of the phase of the ac stress or the phase of a given acoustic response was determined a posteriori using a phase recognition algorithm [13], [14]. In this paper, the ac phase-matching circuit is designed to solve the matching problem, as shown in Figure 1.

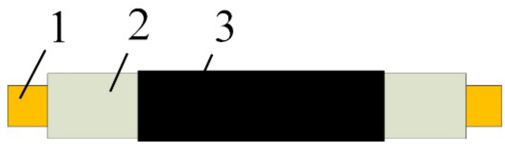
The ac sinusoidal signal obtained from the capacitive voltage divider is transformed into a square waveform signal synchronous with high ac voltage. The square waveform signal triggers the signal generator to output 32 short square waveform signals, which control the switch of high-voltage pulse power supply. Electro-acoustic signals in 32 phase angles can be measured in one sinusoidal period due to the control of phase-matching circuit on high-voltage pulse power supply. Space charge waveforms were produced by averaging more than 500 sinusoidal period in one time, and the averaged space charge profiles in 32 phase angles were achieved with an interval of 11.25°.

In the space charge measurement process, 35kV/mm (r.m.s value) and 50Hz ac electrical field were applied on the XLPE cable peeling samples. Space charge profiles in 32 phase angles were tested intermittently when ac voltage was applied. After stressing under ac electrical field, XLPE samples were placed in short circuit, and the space charge profiles were recorded as a function of time with stress off.

B. ELECTRO-THERMAL AGING PLATFORM

The 10 kV XLPE cable structure is shown in Figure 2. To prevent corona or even flashover, when AC high voltage is applied, the outer semi-conductive layer on both sides of the cable was stripped, the stress-cone was installed along with the anti-corona balls installed at the exposed cores at both ends. The aging test sample is shown in Figure 3. The outer semi-conductive layer portion of the cable was wrapped with aluminum foil so that the outer layer was well grounded.

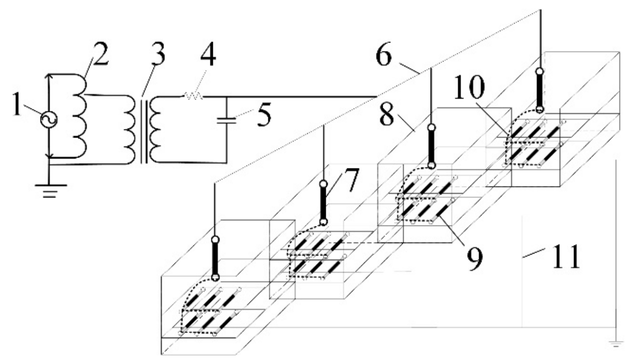
A schematic diagram of the aging platform device is shown in Figure 4.



1. Cable core 2. XLPE insulation 3. Outer semiconducting layer

FIGURE 2. **Cable sample for aging. 1. Cable core 2. XLPE insulation 3. Outer semiconducting layer.**

FIGURE 3. **Figure of the cable installed with a stress cone.**



1. Power supply 2. Voltage regulator 3. The step-up transformer 4. Protect resistance 5. Coupling capacitor 6. Guide-bar 7. High voltage bushing 8. Aging box body 9. Cable aging samples 10. Conductor 11. Ground wire

FIGURE 4. **Structure diagram of the electrical-thermal aging system. 1. Power supply 2. Voltage regulator 3. The step-up transformer 4. Protect resistance 5. Coupling capacitor 6. Guide-bar 7. High voltage bushing 8. Aging box body 9. Cable aging samples 10. Conductor 11. Ground wire.**

C. AGING TEST CONDITION

According to the crystallization characteristics of the XLPE, three temperatures of 103 °C, 114 °C and 135 °C were selected for the aging test. The XLPE cable mainly exhibits electrochemical breakdown during operation [15]. Under the combination of long-term electricity and heat, the microstructure of the material is gradually destroyed and degraded until breakdown occurs [16], [17]. If the applied aging electric field is too high, the internal structure of the insulating material may be rapidly destroyed and the cable quickly breaks down.

This type of electric breakdown or thermal breakdown does not conform to the actual aging process of the cable. Therefore, to determine the mechanism of cable aging, the electric field in the accelerated aging experiment should not be excessively high. In this paper, 3 U0, that is, 26.1 kV was selected as the aging voltage.

The aging test was divided into five stages at regular intervals for the space charge testing. The aging time at different temperature is displayed in Table 1.

TABLE 1. The aging time at different temperatures.

Aging temperature	103℃	114℃	135℃
Aging time(days)	375	200	150
Sample interval (days)	75	40	30

III. VARTATION OF THE TRAP LEVEL OF SPACE CHARGE WITH THE DEGREE OF AGING

The XLPE cable slicing was made at each stage of the aging process and exposed to space charge under AC voltage conditions. A 35 kV/mm (effective value) AC electric field was applied to the XLPE cable section and the voltage was applied for 6 hours. By doing so, the AC voltage was removed and the space charge waveform of the XLPE slice was immediately tested. Then, the slice material was shortened, and the non-polarized voltage space charge waveform of the slice was continuously tested during the short circuit to observe the decay of charge with a short circuit time.

The total amount of space charge during the short circuit of the XLPE slice was calculated according to formula (1).

$$Q = \int |\rho(x,t)|\, dx \tag{1}$$

The curves of the total amount of space charge with the short circuit time was drawn to obtain the short circuit charge decay curves. Figure 5 depicts the decay curves of the cable slice short-circuit charges for each of the aging stages at 103 °C, 114 °C, and 135 °C. The short circuit time is 180s, and data processing method is averaging by 500 times. It can be seen from Fig. 5 that the deeper initial charge of the cable slice, the greater the degree of aging degree and the slower the decay rate.

The decay rate of the short-circuit charge can be expressed as the charge decay time constant τ, which is positively correlated with the trap level inside the material. The trap level of the XLPE slice can be studied by calculating the charge decay time constant. The short-circuit charge decays exponentially and fits the curves in Fig.5 according to formula $y = A * \exp\left(-\frac{x}{\tau}\right) + y_0$, which can be used to determine the charge decay lifetimes of cable slices at each of the temperatures and aging stages which are shown in table 2.

According to the model of charge trapping and de-trapping of polymer materials previously proposed [18]–[20],

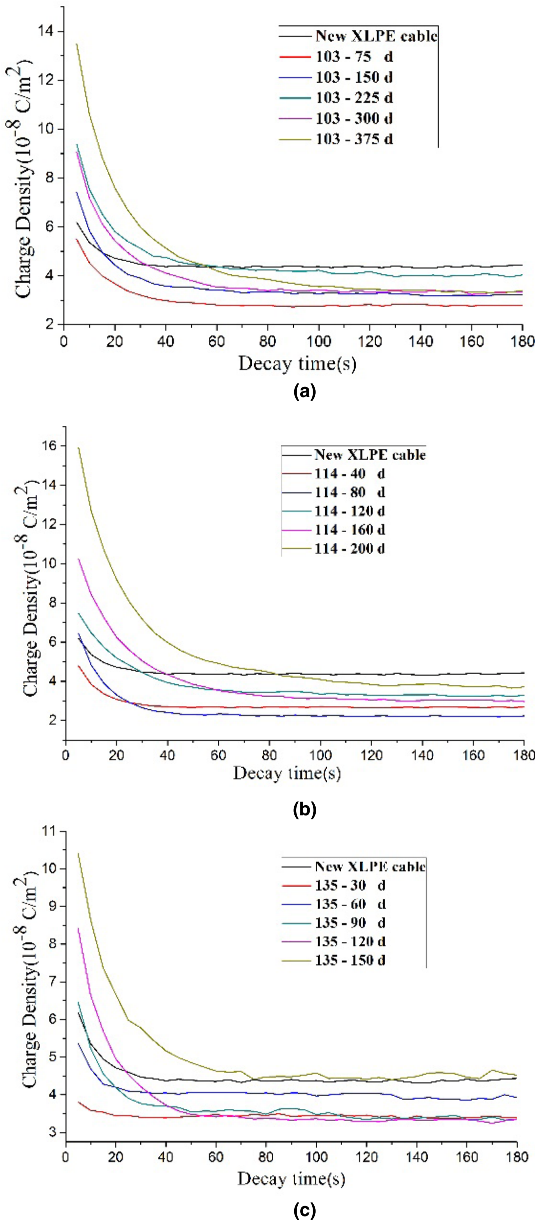


FIGURE 5. The quantity of short-circuit charge for the cable stripped at different aging stages. (a) 103°. (b) 114°. (c) 135°.

the charge decay time constant τ is the reciprocal of the thermal assisted subsidence rate constant kth, and the formula is:

$$k_{th} = \frac{1}{\tau} = N_c v_{th} \sigma_c exp\left[-\frac{E_t}{k_T}\right] \tag{2}$$

We further obtain

$$E_t = kTln(\tau N_c v_{th} \sigma_c) \tag{3}$$

where Et is trap level, k is Boltzmann constant, T is temperature, Nc represents local density of state of conduction band, $N_c = 2(2\pi m_e^* kT/h^2)^{3/2}$, ($m_e^*$ is electronic effective mass, m_e^* ≈me, h is Planck constant); vth is thermal velocity of charge, $v_{th} = \left(3kT/m_e^*\right)^{1/2}$; σc is the capture cross section with a value of 6.5*10-17 m2.

TABLE 2. Attenuation time constants of the XLPE slicing at each aging stage at different temperatures.

	Aging time (day)	Decay lifetime	Standard deviation
New cable		8.82	0.2771
103℃	75	13.1	0.2551
	150	12.3	0.3743
	225	14.8	0.5333
	300	16	0.3913
	375	18.9	0.5026
114℃	40	8.77	0.1328
	80	10.8	0.1290
	120	19.2	0.3245
	160	19.9	0.2530
	200	20.1	0.5036
135℃	30	6.3	1.1542
	60	7.4	0.6963
	90	10.8	0.6009
	120	13.6	0.2004
	150	15.3	0.3405

Figure 6 shows the curves of trap energy levels with aging time of the XLPE slices after aging at 103 °C, 114 °C, and 135 °C. From the figure it can be seen that the trap level of the XLPE slice is around 1.0 eV. When aged under different temperature conditions, the trap level becomes substantially larger as aging time increases. This indicates that the molecular chain of XLPE is broken after electro-thermal aging, and impurities such as cross-linking agents and antioxidants are decomposed and attached to the broken polyethylene molecular chain. The broken molecular chain and decomposition of impurity will damage the structure of molecular chains, making a large amount of chemical bonds fractured and free radical generated. Space charge is easily to be captured by the defects and hardly detrapped, so the trap level will become higher after aging.

In the early aging stage, chain crosslinking in XLPE material has a larger probability of occurrence than chain decomposition. Thus, the defect concentration is reduced in the cable insulation, and the space charge density captured by traps is correspondingly reduced. In the middle and late aging stages, the structure of the molecular chains is damaged. Thus, the defect density increases, thereby increasing the space charge density.

From the above analysis, it is known that the trap levels of the XLPE slices after aging are increased, which improves the ability of the insulating medium to capture space charge. The existence of deep traps causes the electrons to be captured and accumulate. As the aging deepens, the deep traps also increase, which inevitably leads to an increase in the number of electrons remaining in each cycle. Also, the amount of charge accumulates over a long period, increasing the ability

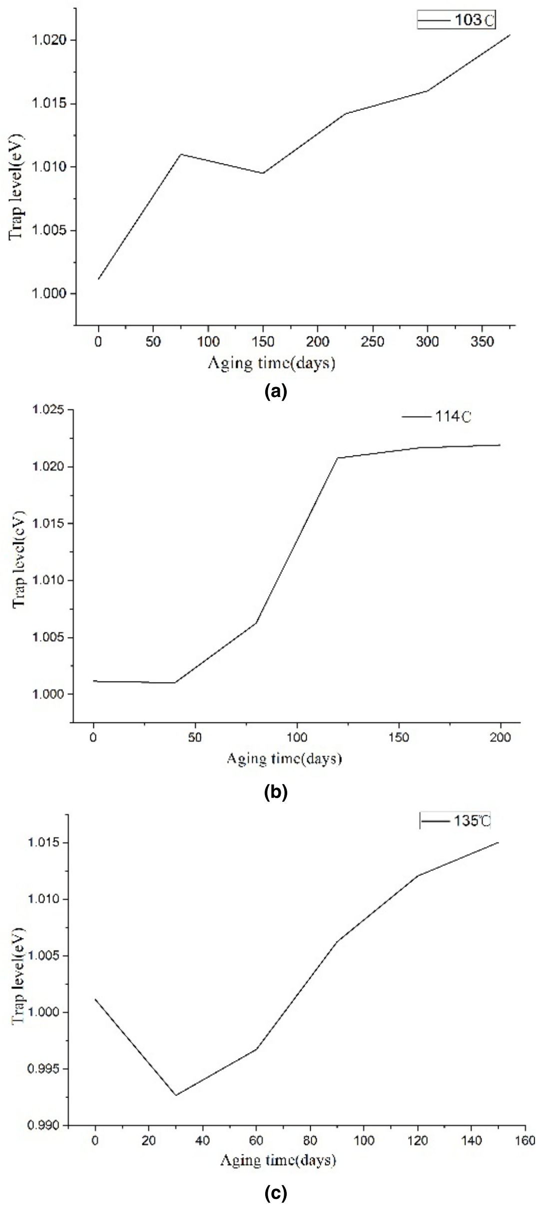


FIGURE 6. Trap energy levels of cable stripped at different aging time. (a) 103°. (b) 114°. (c) 135°.

of the dielectric to accumulate charge. The accumulation of space charge causes electric field distortion and energy transfer and release. Consequently, this destroys the insulation structure through thermal electron theory, photo-degradation theory, extraction and extraction theory, resulting in more deep traps [21]–[24]. The accumulation of charge and the increase in the trap level density form positive feedback are found and the alternating space charge tends to accumulate with aging time.

IV. THE VARITATOIN LAW OF SPACE CHARGE DURING LONG-TERM AC POLARIZATION

To study the space charge characteristics of XLPE under AC voltage, long-term AC polarization experiments were carried out on the aged XLPE sections to test the variation of AC space charge with voltage application. Two electrode models, a plate electrode and a cylindrical electrode, were used to simulate uniform electric and non-uniform electric field environments respectively. The influence mechanism of the electric field environment on the AC space charge was discussed.

A. TEST RESULTS AND DISCUSSION UNDER UNIFORM ELECTRIC FIELD CONDITIONS

Figures 7-9 show the space charge of the sliced XLPE during polarization or depolarization under a uniform AC electric field. Figure 7 shows the space charge curve of polarization for 24 h. Figure 8 shows the space charge curve at 12 days after polarization for 24 hours, and Figure 9 illustrates the space charge curve for depolarization.

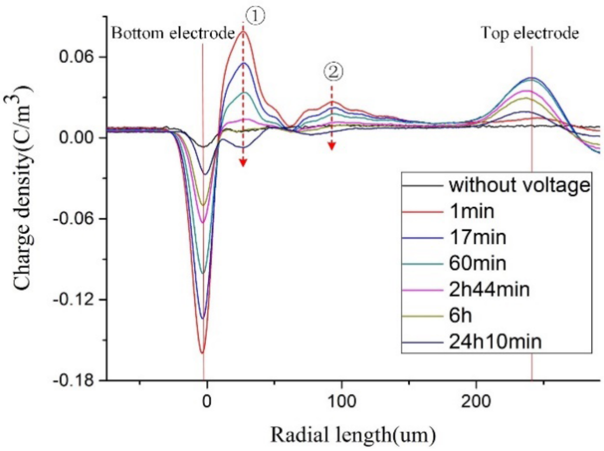


FIGURE 7. The charge change waves in 24 h polarization under a uniform electric field.

From the variation in the space charge density curve in Fig 7, it can be seen that in the polarization experiment, the charge rapidly increases within 1 min to form the bottom electrode interface peak shown as peaks ① and ②. As the polarization time becomes longer, the interface peak, and peaks ① and ② decrease continuously. Peak ① changes from accumulating positive charge to negative charge, which lasts for 24 hours. The space charge distribution after polarization for 24 h is shown in Fig. 8. The bottom electrode interface peaks ① and ② increase continuously, and the negative charge accumulation of peak ① turns into positive charge accumulation.

In the depolarization experiment, the external electric field was removed and the test results are shown in Fig. 9. The charge peak rapidly decays in the first few minutes, and the charge waveform remains substantially unchanged from 6 minutes to 4 hours. By analyzing the charge change and cause of charge migration, it can be seen that at the beginning of the polarization, the rapid ionization of the inside of the medium under the action of a uniform alternating electric field generates a large amount of free charges, which

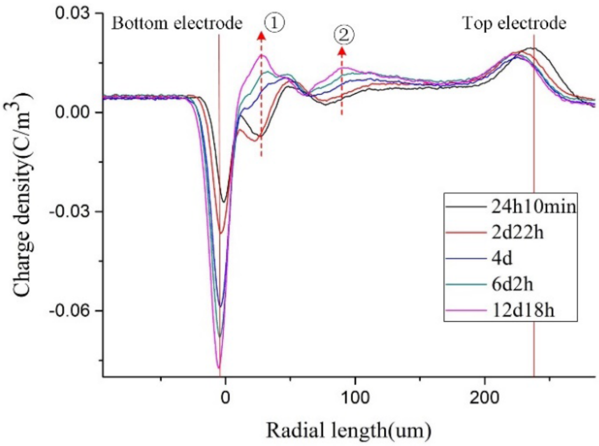


FIGURE 8. The charge change waves after 24 h to 12 days polarization under a uniform electric field.

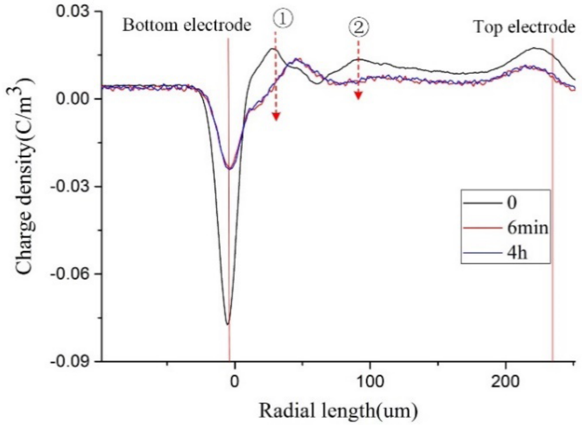


FIGURE 9. Space charge change waves in depolarization under a uniform electric field.

accumulate around the "trap" to form peaks ① and ②, causing distortion of the electric field in the medium.

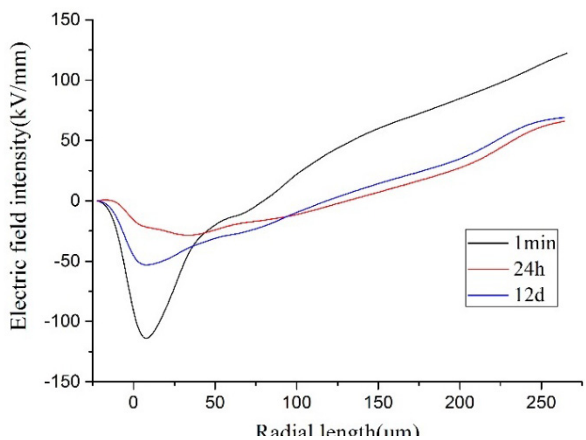


FIGURE 10. The distribution of electrical field intensity at different instants of time.

According to the Poisson equation, the electric field intensity distribution at different times was calculated as shown in Fig. 10. With the process of polarization, a part of the negative charge enters the medium at the interface under the action of the distorted electric field. The negative charge is induced by electromagnetic induction at the lower interface, causing the interface peak to decrease continuously which is constantly connected with peaks ① and ②. The accumulation of positive charge neutralization causes it to decrease continuously. After 24 hours of polarization, the electric field distribution gradually becomes uniform, and the negative charge stops the injection. The positive charge generated by the "trap" at peaks ① and ② continues to capture ionizations, and the positive charge continuously induces a negative charge at the interface peak causing it to increase.

During the depolarization process, the charge trapped by the "shallow trap" dissipates rapidly and the "deep trap" resides in the charge which dissipates slowly. Therefore, the charge still exists after 4 hours in Fig. 9, indicating that there is a "deep trap" in the medium. The ② peak charge still exists after 4 hours of the short circuit, indicating that there is a deep level trap resulting in a long charge residence time.

B. TEST RESULTS AND DISCUSSION UNDER NON-UNIFORM ELECTRIC FIELD CONDITIONS

Figures 11 and 12 show changes in the space charge of the XLPE slices during the polarization process or depolarization under a slightly uneven AC electric field. Figure 11 shows the change of space charge for 3 days during polarization. Figure 12 shows the change of space charge in the depolarization process. As previously described, the two charge peaks inside the medium were numbered ③ and ④.

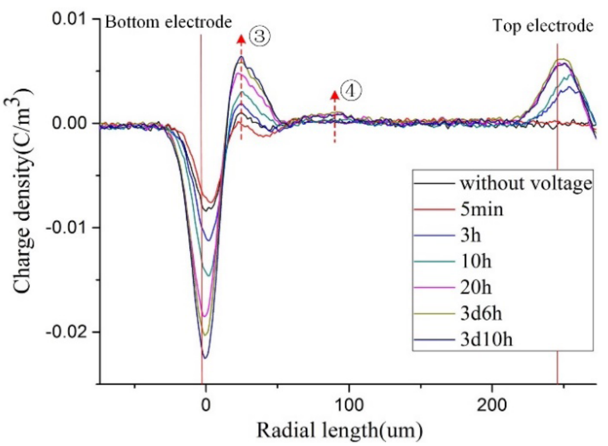


FIGURE 11. Changes in the XLPE slices under an AC non-uniform electric field during periods of polarization.

From Fig. 11, during the polarization process, the interface charge and the ③ peak gradually increase, moving towards the inside of the medium and increasing during the movement. After 3 days of polarization, the charge curve does not change significantly. During the depolarization process, as shown in Figure 12, for the first 3 minutes, the charge quickly dissipates. After 3 minutes, the change of the charge curve is

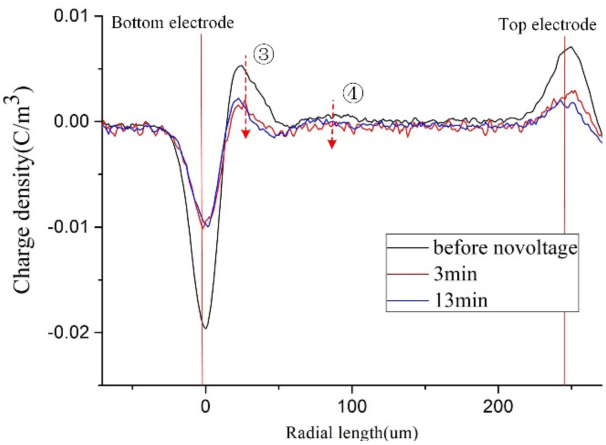


FIGURE 12. Changes in the XLPE slices under AC non-uniform electric field during periods of depolarization.

not obvious, indicating there is a "deep trap" in the medium, and the resident charge dissipation time is longer.

From analysis of the causes of charge change, it can be found that after the start of the polarization, the interface between the medium and the electrode is continuously ionized, generating more positive and negative charges. Under the action of the negative pulse, the negative charge is concentrated at the interface, and the positive charge is gradually formed by the interface which moves through the medium until it moves to the ④ peak position. Due to the injection and migration of charges, the positive charge at the ③ peak gradually increases. At the ④ peak, there is no charge from the beginning until a positive charge occurs. In the depolarization experiment, in the absence of an external electric field, the ③ and ④ peak charges at the interface dissipate into the interface and remain stable after 3 mins.

It can be seen from the polarization experiment described above that the AC space charge does not move under a uniform electric field, but move under a non-uniform electric field. This shows that the non-uniform electric field is a necessary condition for charge transfer in the AC space.

V. CONCLUSIONS

In this paper, an AC space charge experiment of cable insulation slices after electro-thermal aging was performed, from which the following conclusions can be drawn:

1) A short time exchange polarization experiment was carried out on the cable slices at different aging stages. The charge decay curves were drawn during the short circuit and the trap levels were calculated. It was found that the trap levels of the XLPE at three temperatures (103 °C, 114 °C and 135 °C) gradually increased with aging time. This indicates molecular chain breakage of the XLPE under electro-thermal aging, decomposed impurities such as cross-linking agents and antioxidants, and the generation of deeper level traps, resulting in an increase in the trap level of cable insulation.

2) Two models of plate electrode and cylindrical plate electrode were used to simulate the uniform electric field and non-uniform electric field conditions respectively. The long-term AC polarization experiment was carried out on the

cable section after aging, and the change law of AC charge was observed. Under the two electrode models, the changes were obvious within 1-2 days of the pressurization, after which the charge distribution remained largely unchanged. Under the non-uniform electric field conditions, the alternating charge was transferred, indicating the alternating charge transfer is related to the electric field non-uniformity.

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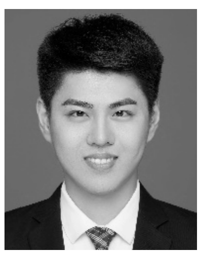

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