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The effect of field caused by space charge on aging exponent of XLPE and nano-XLPE under temperature gradient

Rui **SU**, Ya **Wang**, Yang **WU**, Chuanhui **CHEN**, Kai **WU;** State Key Lab of Elect. Insul. & Power Equip., Xi'an Jiaotong University Xi'an, China
sr871216@stu.xjtu.edu.cn, wy123456@stu.xjtu.edu.cn, wuyang0018@163.com, chengchui1239@163.com, wukai@mail.xjtu.edu.cn

ABSTRACT

This article discusses the aging exponent of XLPE and nano-XLPE under temperature gradient by step-stress test. And the space charge profiles at same conditions were measured via modified pulsed electro-acoustic (PEA) method. Then a recovery method was proposed to obtain accurate field distributions. It was indicated that the relationship between the maximum field calculated from the Poisson equation and average electric field was linear before and after the recovery. Therefore, the distorted electric field caused by space charge might not be the factor leading to large aging exponent of XLPE and nano-XLPE under temperature gradient.

KEYWORDS

Aging exponent, temperature gradient, XLPE, nano-XLPE, pulsed electro-acoustic method (PEA)

INTRODUCTION

With the development of high voltage direct current (HVDC) transmission, considerably more attention has been paid to aging of insulation. And the effect of space charge on the performance of polymeric insulation, such as cross-linked polyethylene (XLPE) has been recognized [1, 2], where the accumulation of space charge will lead to field distortion and accelerate aging. Many methods have been taken to improve the performance of XLPE, like incorporating additives, grafting or copolymerization on polyethylene-based [3, 4]. In this article, the addition of nano particles was used. The inverse power law (IPL), which reflects the service endurance capability of insulation and is used to determine the test voltage for the prequalification and type tests [5, 6], is given as

$$L=t \cdot E^{n} \qquad [1]$$

Where L and n are material constants, t is the time to failure at field E, and the aging parameter n is a constant.

One way to determine the aging parameter is to use constant stress tests at a number of voltages. These tests have a single aging element, high accuracy and a simple test procedure, but the time to failure is much longer at the lower voltages and cannot give us useable data without unjustified extrapolations. As step-stress tests can reduce test time and ensure a quick failure and usable data [7], it was used to estimate the aging parameters of XLPE and nano-XLPE in this work. However, the data analysis was much harder than for constant-stress tests, so a new method was used to extract the exponent n of the inverse power to avoid some of the approximations and limitations [8].

In a DC field space charge will develop during the step-stress tests, though the space charge magnitude and distribution are unlikely to come into equilibrium with the applied voltage on any step because of the limited time available at any particular voltage step. The distribution of space charge will change over aging time, as a result of such processes as charge injection, conduction, trapping and de-trapping, and in turn aging will affect the space charge distribution [9] and the energy states of trapped charges [10]. This means that not only will the applied field changes systematically during the step tests, but also that the field distribution may change depending upon the accumulation of space charge, with a consequent influence upon local aging. In order to have a clearer idea as to the actual internal conditions of the sample during the step-tests, it is therefore necessary to carry out complementary experiments to measure the space charge distribution.

Within PEA measurement, the signal at the electrodes was too large to make the space charge near the electrode measured accurately, thus a recovery method was proposed to obtain the accurate field distribution at the interface. The results showed that the relationship between the maximum field calculated from the Poisson equation and average electric field was linear before and after the recovery. So the distorted electric field caused by space charge might not be the factor leading to large aging exponent of XLPE and nano-XLPE under temperature gradient.

EXPERIMENTAL

Step-stress test

Film samples of 0.5mm thickness were made from XLPE and a nano-filled XLPE (1.0 wt% surface treated SiO_2 nano-filler added to type 101B material) for step-voltage stress tests. Prior to testing, the samples were heated for 48 h at 80 ℃ in a vacuum oven to reduce the effect of cross linking byproducts and to ensure uniform initial conditions. A step-stress test system suitable for different temperature gradients was produced by the design of hollow upper and lower electrodes with constant temperature circulating oil bath (Figure 1). The samples

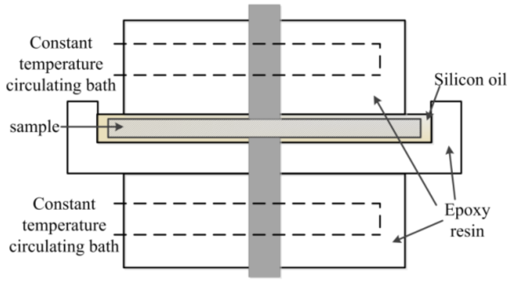


Fig. 1: The apparatus of aging tests under different temperature gradients

were totally immersed in silicone oil to exclude the effect of air and avoid edge effect.

In our study, step-stress test was conducted at three temperature gradients (TG = 0, 20 and 40 ℃) respectively. The temperature of lower electrode was maintained in 20 ℃, and upper electrode was set to be 20 ℃, 40 ℃ and 60 ℃ separately. Under each TG, three tests with different dwell times are carried out and the dwell times are set to be 1min, 5min and 25min separately. Six samples are tested for each dwell time. During the experiments, the initial voltage is 10kV, the voltage step is 5kV and the rate of voltage ramp-up is 1kV/s. The extraction method of the IPL aging parameter was the same with that in [8].

Space charge measurement

To demonstrate that a temperature gradient affects the space charge accumulation under DC stress, space charge profiles in XLPE and nano-filled XLPE at 10, 20, 30, 40 and 50kV/mm under DC step-stress, with the dwell time 25 min, and for TGs of 0, 20 and 40 ℃ were measured. As the same with the step-stress test, hollow upper and lower electrodes with constant circulating oil bath were added to form TG. The PEA measurement system was displayed in Figure 2.

In our experiments, the temperature of lower electrode was maintained in 20 ℃ and upper electrode were set to be 20 ℃, 40 ℃ and 60 ℃ separately to form different TGs. And all measured data were recovered according to the calibration algorithm described in [11] to account for the effects of attenuation and dispersion.

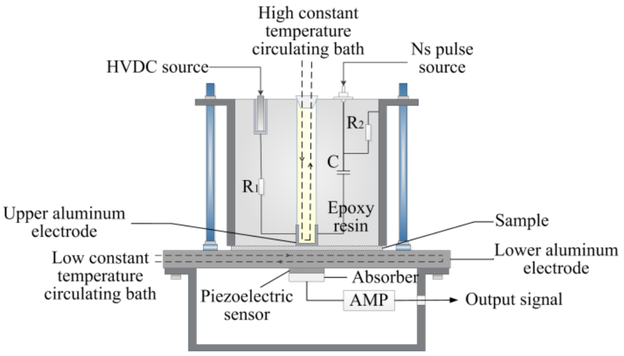
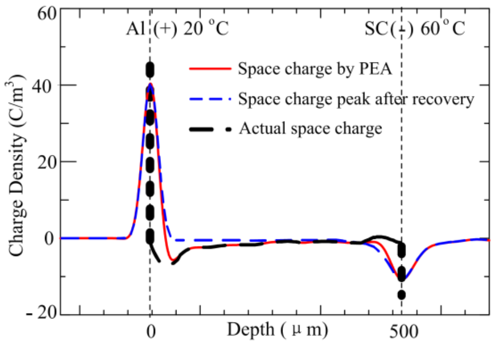


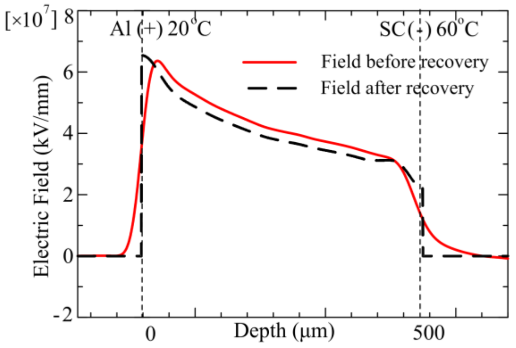
Fig. 2: PEA measurement system under different temperature gradients

Charge and Field recovery

Within the PEA measurement method, as the signal is not ideal square wave and actually has a certain width of rising edge and falling edge, the signal at the electrodes might be too large and cover the space charge accumulation near the electrodes. Thus the space charge accumulation near the electrodes was possibly not correct. To recover the space charge distribution, firstly recover the space charge peak at the electrode. The actual peak is symmetrical at the electrode, so flipping the outer half electrode peak to the inside part. Then remove the space charge peak at the electrodes from the space charge wave, as Figure 3(a) shows. Finally the space charge inside sample can be obtained. And the corresponding electric field distribution can be calculated from Poisson equation, as in Figure 3(b)).



(a) Space charge recovery



(b) Electric field recovery

Fig. 3: Space charge and electric field recovery: (a) space charge recovery; (b) electric field recovery

RESULTS AND DISCUSSION

The aging parameters of XLPE and nano-XLPE under different temperature gradients were shown in Figure 4. Clearly, the value of aging exponent of IPL increased with increasing TG for both XLPE and nano-XLPE. Besides, the value for the nano-XLPE was lower than that for XLPE at all TGs, which might be due to the suppression of space charge accumulation after the addition of nano particles.

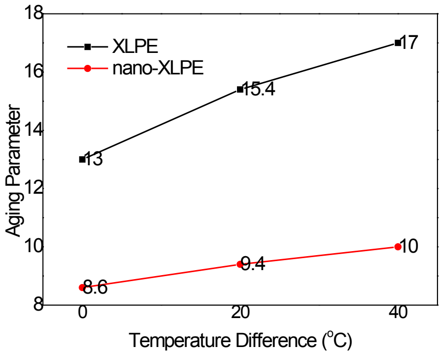
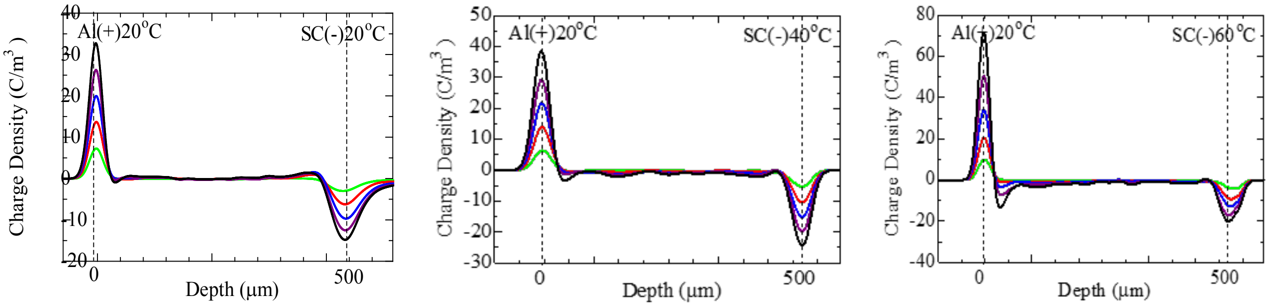
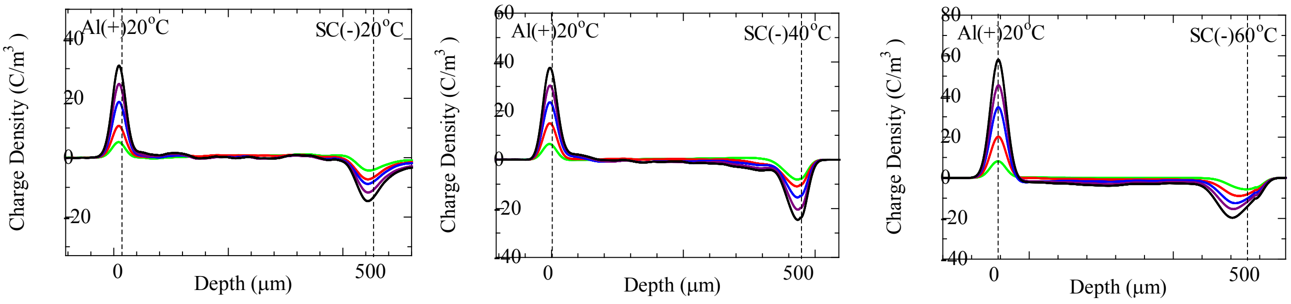


Fig. 4: The IPL aging exponent for XLPE and nano-filled XLPE under a temperature gradient.

Meanwhile, the space charge profiles of XLPE and nano-XLPE under temperature gradient was displayed in Figure 5. It can be seen that the accumulation of space charge was enhanced with the increasing TG both for XLPE and nano-XLPE, which was corresponding to the increasing IPL aging exponent. In XLPE, due to the hetero-charge peak near the low temperature electrode, the electric field near the low temperature electrode was enhanced



(a) XLPE

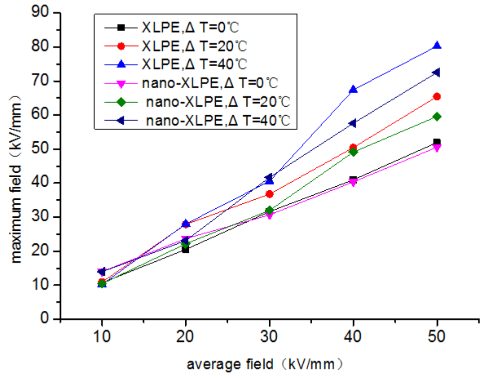


(b) Nano-XLPE

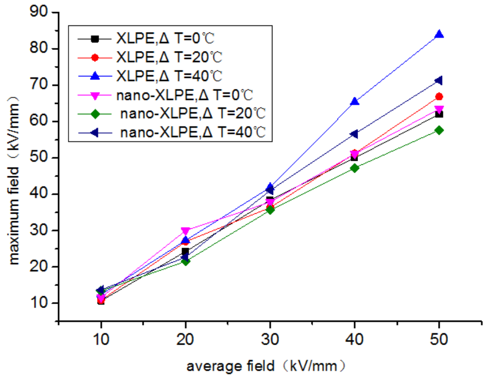
Fig. 5: Space charge distribution in (a) XLPE (for AC) and in nano-filled XLPE (1.0 wt% surface treated SiO_2 nano-filler) as a function of 0, 20 and 40℃ temperature gradients.

thereby giving rise to a lower breakdown value and lager aging exponent of IPL. And there was less space charge accumulation in the nano-XLPE, resulting in lower IPL aging exponent of nano-XLPE.

Furthermore, the maximum electric field was calculated from the Poisson equation, and the relationship between the maximum field and average electric field at various TGs was shown in Figure 6, (a) displayed the relationship before field recovery and (b) after recovery. It was indicated that the relationship between the maximum field and average electric field was linear, and the distorted field caused by space charge might not be the factor leading to large IPL aging exponents of XLPE and nano-XLPE.



(a) Before recovery



(b) After recovery

Fig. 6: The relationship between the maximum field and average electric field before and after recovery: (a) before recovery; (b) after recovery

CONCLUSIONS

The results of step-stress tests showed that the IPL aging exponent both for XLPE and nano-XLPE increased with the increasing temperature gradients but the IPL aging exponent for XLPE was larger than that of nano-XLPE. And the space charge measurement at the same conditions explained this phenomenon where there was more space charge accumulation in XLPE than in nano-XLPE. After the recovery of space charge distribution, the accurate electric field distributions were obtained. It was indicated that the relationship between the maximum field calculated from the Poisson equation and average electric field was linear before and after the recovery. Therefore, the distorted electric field caused by space charge might not be the factor leading to large aging exponent of XLPE and nano-XLPE under temperature gradient. Further studies are needed to investigate the factor resulting in this phenomenon.

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