Space charge dynamics in epoxy resin under voltage polarity reversal at various temperatures

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1 | INTRODUCTION

Energy resources in China are unevenly distributed. Coal is distributed mainly in the north and north-west regions, and water in the south-west region. However, most of the energy consumers are located in the eastern area. Long distance transmission of power is an effective method of solving this imbalance. A number of ultra-high voltage (UHV) direct current (UHVD, ±800 kV) lines have been built or are under construction. UHVD dry-type bushings, whose main insulation material is epoxy resin impregnated paper, are widely used in these lines.

In addition to DC and AC operating voltages, dry bushings in normal service also have to withstand the polarity reversal voltages generated by reversal of power flow or other fast voltage changes. In order to assess the insulation strength of bushings, a polarity reversal test is necessary. According to standard IEC/IEEE 65700 [1], polarity reversal tests should be performed at low temperature (10°C–40°C). However, the extremely large current flowing through the central conductor of the bushing in normal service would lead to central conductor temperatures in the approximate range 90°C–105°C when working at maximum power flow [2]. Such temperatures would severely stress the inner insulation of the bushings.

The polarity reversal test [1] was initially introduced to assess the ability of the oil-paper insulation in converter transformers to withstand stresses imposed by polarity reversal or other rapid voltage changes [3–5]. Qi Bo, Du Boxue and co. found that the charge accumulation and dissipation at the interface of oil-paper insulation show a polarity effect under voltage polarity reversal [6,7]. For polymer insulation materials, the energy released during space charge injection, extraction or neutralization can lead to local degradation of polymer, such as electric tree, and so on. Dissado et al. investigated the decay of space charge in a glassy epoxy resin following voltage removal and proposed a space charge decay model with a uniform energy distribution [8]. Tzimas et al. study the effect of DC poling duration on space charge relaxation in virgin XLPE cable peelings by using above space charge decay model and found that the poling durations affect the amount of charge.

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trapped in different trap depth range [9]. Luo Yi, Tang Ju and et al. studied the dynamics of surface charge and electric field distributions on basin-type insulator in GIS/GIL under voltage polarity reversal and found that voltage polarity reversal has no additional influence on insulation performance of basin-type insulator [10]. Wang shaoho, Tu Youping and et al. studied the effect of polarity reversal on space charge properties of CB/LDPE composite and found that CB nanoparticles can inhibit the space charge accumulation after the voltage polarity reversal [11]. Tanaka et al. found that the packet-like charge generated in XLPE under voltage polarity reversal, whereas the packet-like charge was not observed in a modified XLPE [12]. Although the Maxwell-Wagner (MW) polarization model is used to study the dynamic characteristics of the interface charge of multilayer dielectric, some experimental results are not always consistent with the MW model. Our previous research work has shown that below 60 °C, the interfacial charge density of the epoxy resin impregnated crepe paper calculated according to the MW model is consistent with the measured value, while above 60 °C, it is smaller than the measured value [13]. In order to overcome the shortages of the MW model and bipolar charge transport model, Liang Hucheng, Du Boxue and et al. proposed an improved space charge transport model in bi-layer dielectrics [14].

Although the effects of voltage reversal on the space charge and electric field profiles in polymer materials have been investigated, the research work on space charge dynamics in epoxy resin used in dry-type bushings under polarity reversal at various temperatures still requires further in-depth analysis. In this article, we focus on the evolution of space charge and electric field distributions in epoxy resin samples during the polarity reversal test, at temperatures in the range 40 °C–100 °C.

2 | EXPERIMENTAL

2.1 | Preparation of samples

The matrix resin was bisphenol-A diglycidyl ether E51, with an epoxy loading of 0.48–0.54 g per 100 g of matrix, following [2] and [13]. The anhydride hardener (methyl hexahydrophthalic anhydride) and catalyst (N, N-dimethyl benzyl amine) were then added to the matrix resin with mass ratios 100:85:0.3 of epoxy, hardener and catalyst, respectively. The mixture was stirred at room temperature for 1 h and degassed at 55 °C for about 6 h in a vacuum oven. Finally, the mixture was poured into a steel mould and cured at 65 °C for 5 h, then at 110 °C for 10 h, 145°C for 15 h and finally at 120 °C for 10 h. The dimensions of the samples were 110 × 110 × 0.24 mm. The glass transition temperatures ($T_g$) of three samples measured using a differential scanning calorimeter DSC822e with a temperature ramp of 10 K/min were approximately 140 °C.

2.2 | Space charge measurement

Polyvinylidene fluoride-trifluoroethylene P(VDF-TrFE) piezoelectric film with a Curie temperature of 135 °C ± 5%, and in which piezoelectricity is stable about 110 °C, was used as the piezoelectric transducer in the pulsed electro-acoustic (PEA) space charge density profile measurement system. Thus the space charge profiles of the samples could be safely measured at temperatures up to 100 °C. The transducer was not in physical contact with the sample, but was attached to the surface of the lower electrodes of PEA system. The temperatures of metal parts in contact with insulating material in resin-impregnated paper bushing should not exceed 120 °C under normal operating conditions, according to standards [1] and [15]. The highest temperature of insulating material in dry-type bushing was actually controlled no more than 105 °C when we designed the dry bushings, that is, the highest temperature in UHV bushing measured in the temperature rise test, for a current of 3150 A through the inner conductor of the bushing, was about 95 °C, and located at the inner conductor of the bushing [16]. Thus, the results of space charge and electric field distribution in epoxy resin measured in the present work can reflect the behaviours of space charge in the UHV bushing under polarity reversal at high temperatures in service to some extent.

In order to ensure good contact between the electrodes and the samples, both sides of the samples were sputtered with gold, with a diameter of about 16 mm and a thickness of 240 μm. The upper electrode (upper) was carbon-loaded semi-conductive material, and the lower electrode (GND), which was grounded, was aluminium. The high voltage (positive and negative polarity) was applied to the upper electrode. The samples were sandwiched between these electrodes. The samples were immersed in silicone oil during the measurements in order to avoid partial discharge. Further details of the PEA system have been reported in [2].

The width of the high voltage pulse at half-height was about 5 ns, and the sound velocity in epoxy resin is approximately 2250 m/s, so that the spatial resolution of the space charge measurements is approximately 11 μm, that is, approximately 5% of the sample thickness, which complies with the recommended range of the standard IEC TS 62758 [17].

2.3 | Polarity reversal test

A double polarity reversal test was recommended by the IEEE Working Group on Dielectric Tests for HVDC Stressed Transformers and Reactors [4]. The polarity reversal test adopted in the present work, consistent with [1], is shown in Figure 1. The test sequence consisted of 90 min at negative polarity, followed by 90 min at positive polarity, and finally 45 min at negative polarity. According to Equation (1) each polarity reversal is to be completed within 2 min. In real HVDC transmission systems, polarity reversal is performed according to the power management requirement, and the polarity reversal period is variable. Following [18] and [19], we fixed the reversal period at 60 s.

A waveform generator and a Trek high-voltage power amplifier (Model 30/20A) were combined to generate polarity reversals accurately. Two different electric field strengths, 10 kV/mm and 20 kV/mm, were applied to the samples at temperatures of 40 °C, 60 °C, 80 °C and 100 °C. The frequency of
the high voltage pulse is 154 Hz, and an average over 128 measurements was used in order to improve the S/N ratio. The averaged data were recorded by a computer every 1 s during reversal periods II and IV, and every 5 s during periods I, III and V.

3 | RESULTS AND DISCUSSION

3.1 | Polarity reversal test

Figures 2 and 3 show the evolutions of the space charge profiles of the epoxy resin samples during the entire polarity procedure, respectively under applied electric fields of ±10 and ±20 kV/mm, at temperatures of 40°C, 60°C, 80°C and 100°C. In the Figures, the white dashed vertical lines indicate the positions of the electrodes, and the white dashed horizontal lines indicate the beginning and end of each reversal period. In order to clearly show the evolution trends of the space charge profiles during the test, the red dashed lines with arrows were added in Figures 2 and 3. The red dashed lines represent the outlines of the space charge profiles that were just clearly distinguished in the sample bulk by the PEA system.

As shown in Figure 2a,b and Figure 3a,b, the red dashed lines are almost vertical during the entire polarity reversal test, which means that the evolutions of space charge in the sample bulk were hardly distinguished by PEA system with the field applied. The penetration depth of space charge injected from the electrodes was less than spatial resolution of the PEA system at temperatures no more than 60°C. The red dashed lines in Figures show that the space charge contours are slightly displaced from the electrodes towards the interior of the sample. Such displacements are more clearly seen in Figure 2d and Figure 3c,d. During period I at negative polarity, homo-charge injection from both electrodes in Figures 2d and 3c seemed to need more time to reach a steady state than in Figure 3d. It would be expected that the steady state time would depend on temperature and applied voltage. As space charge injection from the electrodes was not visible in Figures 2a,b and 3a,b, it is difficult to determine the steady state time in period I or III at temperatures no more than 60°C. As depicted by the red dashed lines in the Figures 2d and 3c,d, the space charge from period I did not completely dissipate after period I, and then became hetero-charge in period III. Consequently, the evolutions of homo-charge profiles during period III were different from that in period I.

Compared with 10 kV/mm, the evolutions of the space charge profiles under 20 kV/mm were more obvious at high temperature. The space charge profiles during the reversal period II and IV at various temperatures in Figure 3 were plotted in Figures 4 and 5 respectively. The polarity reversal time 0–60 s in Figures 4 and 5 corresponds to the reversal period 5400–5460 s or 10,860–10,920 s in Figure 1. Because the width of the external high voltage pulse was not zero (about 5 ns at half-height), the signals from the surface charge on the electrodes were not ideal Dirac delta signals, but pulse signals. In measurements under voltage, the pulse signals due to the charge on the electrodes would overlap those due to the space charge in the bulk, so that the latter would hardly be visible. The main indication of the presence of homo-charge is then a small displacement of the space charge profile from the electrodes into the sample [8].

At temperatures of 40°C and 60°C in Figure 4, the charge peaks coincided with the electrode position before and after the reversal, which indicates that the space charge injection was not obvious. At t = 30 s, although the applied field had dropped to zero, the charge density at electrodes was not zero, which polarity was the same as that of applied voltage before the reversal. Moreover, the peak value of space charge profiles at t = 60 s was always slightly smaller than that at t = 0 s.

At temperatures of 80°C and 100°C in Figure 5, before the reversal, there was a small displacement of the space charge profile from the electrodes into the sample, which indicates that homo-charge was injected from both electrodes into the sample bulk. After the reversal, the homo-charge accumulated in the samples became hetero-charge, and the charge on the electrodes was induced by the hetero-charge and applied voltage, which lead to the amplitude of the profiles at 60 s was greater that at 0 s. At 30 s, there were obvious mirror charge peaks on both sides of the electrode. The homo-charge injected at 80°C and 100°C cannot be completely dissipated during the reversal period II and IV.

3.2 | Charge dynamics during polarity reversal

Charge accumulation and dissipation in a polymer are influenced by several factors, for example, dispersion effect of conductive carrier, temperature, applied electric field, electrode material and additives. In Figure 4a–d, the evolutions of the space charge profiles cannot be attributed to the space charge injection at temperatures of 40°C and 60°C. Considering electrode GND which has positive polarity during period I, positive charge will be induced on it by the applied voltage. Homo-charge injected into the bulk during period I will be positive charge and will induce negative charge on electrode GND. At t = 30 s during the reversal, the charge induced on the electrode by the applied voltage will be zero, so the net charge on the electrode will then be negative, and
Figure 2: Space charge evolution during the entire polarity reversal test under an electric field of 10 kV/mm. (a) 40°C, (b) 60°C, (c) 80°C, and (d) 100°C.

will become more negative as the electrode becomes negative at \( t > 30 \) s. However, the results measured in the experiment was not consistent with the above description, which shows that other physical processes occurred in the epoxy samples during the polarity reversal test. Epoxy resin is a kind of amorphous material, and its conductivity will increase significantly under high applied field. The hopping conduction is one of the conductance processes of epoxy materials, and a low-frequency dielectric relaxation will occur due to the dispersion effect of charge carriers in the hopping conduction [20,21]. If the electrical relaxation time of the low-frequency dielectric relaxation is close to the reversal period, the relaxation process would affect the charge induced on the electrodes during the reversal. At \( t = 30 \) s during the reversal, although the applied voltage was zero, the charge induced on the electrode by the low-frequency dielectric relaxation was not zero, and its polarity was the same as that of the applied voltage before the reversal, which neutralized the charge induced on the electrode by the applied voltage at \( t > 30 \) s. When the polarity reversal was completed, the low-frequency dielectric relaxation had not yet been fully established, which make the net charge on the peak value of space charge profiles at \( t = 60 \) s was always slightly smaller than that at \( t = 0 \) s.

In Figure 5a–d, the homo-charge injection appeared in the epoxy samples at temperatures of 80°C and 100°C. As the distance between the space charge peak and the neighbouring electrode was short enough, the injection, extraction or neutralization of space charge mainly happened at the interface regions of the sample bulk adjacent to electrodes during the polarity reversal test.

The homo-charge accumulated in the bulk of EP samples was injected from the neighbouring electrode, which maybe obey the Schottky injection model. If an electric field is applied, the height of the potential energy of the electron injected from the electrode is modified by

\[
\Delta_i = eEx
\]

(1)

where \( e \) is the electronic charge, \( E \) is the Poisson field between the electrode and the EP sample that influences electron emission, \( x \) is the distance from the interface between the electrode and the EP sample.
The maximum of $x$ can be determined by [22]

$$x_{\text{max}} = \left( \frac{e}{16\pi\varepsilon_0\varepsilon_rE} \right)^{\frac{1}{2}}$$

(2)

where $\varepsilon_0$ is the permittivity of vacuum, $\varepsilon_r$ is the relative permittivity of the EP sample. If $E = 20$ kV/mm, $\varepsilon_r = 3.6$, then $x_{\text{max}} = 3.16$ nm. The reduction of the barrier height under 20 kV/mm is 0.063 eV. With the accumulation of homocharge, the electric field $E$ at interface decrease, which leads to a smaller reduction of the barrier height.

The de-trapping process of space charge after the polarity reversal would be governed by a thermally activated process, which obeys the Pool–Frenkel model and can be expressed as follows:

$$P_{\text{de-trap}}(E \neq 0) \propto e^{-\frac{(x_{\text{max}} - d)}{kT}}$$

(3)

where $P_{\text{de-trap}}$ is the de-trapping probability of space charge, $E$ is the Poisson field that influences charge de-trapping, $\Delta$ is the trap depth (or activation energy), $q_e$ is electric charge, $d$ is the distance from the centre of the trap to the peak of the barrier, $k$ is Boltzmann’s constant, $T$ is the temperature and its unit is K.

By molecular simulation, it was revealed that the traps within the polymer may be divided into two groups, namely shallow and deep. The depths of shallow traps are 0.1–0.5 eV and ones of deep traps are around 1 eV to a few eV [23]. Physical defects, for example, conformational defects, tend to generate shallow traps [24], while chemical defects, for example, broken bonds and impurities, tend to generate deep traps [25]. In addition, Dissado has found that the traps within the glassy EP are associated with the hetero-atoms of the chemical structure [8]. So, the traps depths within the epoxy sample may be also in the range of around 1 eV to a few eV. Takada et al. investigated the trapping sites in chemical structures of polymers by quantum chemical calculation and found that the radius of the circle for an equipotential of 1 eV is on the order of a few nanometres [26]. If the radius of the equipotential circle of 1 eV is taken as 5 nm in this study, the barrier reduction of the single-valence trap under the applied electric field can be calculated by the formula:

$$\Delta_v = q_e Ed$$

(4)
According to Equation (4), the barrier reductions are 0.05 and 0.1 eV under applied electric field of 10 and 20 kV/mm, respectively. Compared with the depth of 1 eV, the barrier reduction of deep trap due to applied electric field is much smaller and has little effect on charge de-trapping in deep traps.

According to the above analysis, the barrier reduction due to the applied electric field is small in both Schottky and Pool–Frenkel model. If the homo-charge injection is regarded as an equivalent hetero-charge extraction, the space charge injection and extraction are both mainly governed by a field-independent thermally activated process. Neglecting the transport of the charge to the electrode for neutralization, the de-trapping process can be described by a decay model with an essentially uniform energy distribution proposed by Dissado.
The details of this model are given in [8], and the depth (Δ\text{max}) of deepest traps can be determined by

\[ Δ_{\text{max}} = \frac{kT \ln(νt_{\text{max}})}{1.6 \times 10^{-19}} \]  

(5)

where ν is the attempt to escape frequency, t_{\text{max}} is the time at which the deepest traps start to be emptied. ν can be estimated by ν = kT/h.

According to Equation (5), if the depth of the deepest trap is 1 eV, t_{\text{max}} required for charge de-trapping is less than 5s, which is less than the sampling interval time during periods I, III and V. We therefore assume that the space charge measured using the PEA method are all trapped in deep traps, with depths of around 1 eV. In this work, we cannot distinguish accurately between charge on the electrodes induced by the applied voltage and space charge within the sample bulk adjacent to the electrodes. The accurate dissipation time t_{\text{max}} of the hetero-charge is not readily deduced only from Figures 2 and 3. In order to more accurately investigated the characteristics of space charge injection and dissipation under polarity reversal, the transient processes of the space charge evolutions will be analysed in term of the position variations of maximum electric field strength in the next section.

3.3 Electric field distortion during polarity reversal

Using the space charge density measured by the PEA system, the Poisson field E(\delta) at distance x from the GND (lower) electrode can be calculated from

\[ E(x) = \frac{1}{\varepsilon_0\varepsilon_r} \int_0^x ρ(x)dx \]  

(6)

where ρ(x) is the charge density in the sample.

Since the evolutions of space charge profiles with under 10 and 20 kV/mm are similar, only the evolution of the electric field distribution in the samples during the reverse polarity periods at various temperatures under 20 kV/mm are shown in Figures 6 and 7. The electric field distribution within the samples, at each temperature and each applied field strength, was calculated using the space charge data showed in Figures 4 and 5 respectively.

As shown in Figure 6a–d, at temperatures no more than 60°C, the electric field distribution before and after the reversal was relatively uniform, but the electric field strengths before the reversal (t = 0s) were always slightly greater than those after the reversal. The reason is that the electric field distribution profiles in Figures 6 and 7 were calculated according to Equation (1), in which the influence of the low-frequency dielectric relaxation process was not considered and ε_r was taken as a constant with time. Considering that the low-frequency dielectric relaxation process in high field cannot keep up with the polarity reversal, ε_r after the reversal would become smaller than before the reversal. So, if ε_r before the polarity reversal was used for the calculation, the calculated values of the field strength in Equation (6) after polarity reversal would be smaller than the actual values.

As shown in Figure 7a–d, at temperatures no less than 80°C, especially at 100°C, the electric field distributions in the sample bulks before and after the reversals were different, as shown in Figure 7. A bulge appeared on the contours of electric field profiles before the reversals, and then those contours turned into saddle-shaped after the reversals. The electric field distributions before and after the reversal were no longer uniform. Before the reversal, the maximum electric field in the samples appeared in the central region, which can be more clearly observed at 100°C. After the reversal had just been finished, the maximum electric fields appeared at the interfaces with electrodes for some time thereafter. The distortions of electric field distribution before and after the reversal were caused by the space charge accumulation. Before the reversal, the injected homo-charge from electrodes enhanced the electric field in the central region of the sample bulk. After the reversal, the previously injected homo-charge became hetero-charge and enhanced the electric field at the interface of the sample bulk adjacent to electrodes.

The space charge distorted the electric field distributions within the samples and the following equation defined the electric field distortion rate:

\[ R_d = \frac{|E_{\text{max}}| - |E_a|}{|E_a|} \times 100\% \]  

(7)

where R_d is electric field distortion rate, E_{\text{max}} is the maximum value of the electric field in the sample before the reversal (t = 0s) and after the reversal (t = 60 s), and E_a is the average value of applied electric field.

The electric field distortions within the samples before and after the reversal at various temperatures under 20 kV/mm were calculated by using Equation (7), which results are shown in Figure 8.

It can be seen from Figure 8 that the low-frequency dielectric relaxation had a greater impact on the electric field distribution after the reversal at temperatures no more than 60°C, and the absolute value of the electric field distortion rate after the reversal increased slightly as the temperature raised. This may be caused by the slight increase in low-frequency dielectric relaxation with increasing temperature. After the temperature was above 80°C, the effect of space charge on electric field distortion became obvious. Especially at 100°C, the electric field distortion rate after the second reversal increased significantly.

In addition to the field strength, insulation failure is related to the position of the maximum field strength E_{\text{max}}. Figures 9 and 10 show the position variation of E_{\text{max}} with time during the polarity reversal test at different temperatures. Due to the noise of PEA system, the positions fluctuated in a short time.
scale in Figures 9 and 10, but regularity would show in a long-time scale.

As the electric field distributions were always uniform during the test at temperatures no more than 60°C, no auxiliary lines were added in Figure 9a,d.

At temperatures no less than 80°C, the position distributions of $E_{\text{max}}$ appeared to change with time. In order to better demonstrate the change regularity, several auxiliary red dashed lines were added along the outlines of the position distributions in Figure 10a–d. The vertical red dashed lines represent the distribution range of $E_{\text{max}}$ in the sample bulk after space charge accumulation had reached a steady state in period I, III and V. The oblique red dashed lines represent the outline of the position distributions of $E_{\text{max}}$ during the transient process before space charge accumulation had reached a steady state. The intersections of the vertical lines and the oblique lines
indicated that the transition process had finished, which time was marked by the green dashed lines. After the reversal, \( E_{\text{max}} \) appeared firstly at the interfaces adjacent to the electrodes. When \( E_{\text{max}} \) began to appear again in the central region of the sample bulk, it might mean that most hetero-charge had been extracted or neutralized by injected homo-charge, where time was marked by the blue dashed lines in Figure 10. The middle instant of period II and IV were marked by a black horizontal line, which mean that the applied voltage was just zero.

At temperatures no less than 80°C, the transient process in period I consists of only one process, while the transient process in period III can be divided into two processes, as shown in Figure 10c,d (except for Figure 10a). In the present work, the two processes in period III were divided into the hetero-charge neutralization (or injection and extraction) process (denoted as Prc-I, Blue dashed line in Figure 10) and the homo-charge accumulation process (denoted as Prc-II, green dashed line in Figure 10) respectively. In process Prc-I, the most of hetero-charge trapped before the reversal was extracted or neutralized by the homo-charge injected after the reversal. In process Prc-II, the homo-charge accumulated again in the sample bulk and the charge density reached a steady state at the end of Prc-II. The transient process in period V consisted of the similar transient processes as in period III, but the second process (Prc-II) had not finished before the end of the polarity reversal test. The time of the start, stop and duration of each transient process are listed in Table 1. If the effect of the applied electric field on the barrier reduction of the trap in EP samples is ignored, the space charge evolution in the samples during the entire polarity reversal test can be regarded as a field-independent thermally activated process. Taking the duration of each transient process as \( t_{\text{max}} \), the depths (\( \Delta_{\text{max}} \)) of the deepest traps in the EP samples can be calculated according to Equation (5), which results are also listed in Table 1.

In Table 1, the time of hetero-charge dissipation in Prc-I of Period III was less than that of homo-charge accumulation in period I. The whole transient duration (Prc-I + Prc-II) in period III was less than 2 times of transient duration in period I correspondingly. The trap depth in Period I was always slightly smaller than that in Prc-I. The reason was that the hetero-charge distorted and enhanced the electric fields at the interfaces adjacent to the electrodes after the reversal, which reduced the barrier height of the trap and then accelerated homo-charge injection and hetero-charge extraction in period III. In period V, the transient process Prc-II did not finish after the reversal test had been done. Therefore their stop time cannot be listed in Table 1.

Under 10kV/mm at 80°C, the duration transient process Prc-I in period IV was less than 30 s, which may be caused by that limited resolution of the PEA system. Since more space charge had been injected in period I under 20kV/mm at 80°C, the duration of Prc-I in period III was significantly extended to 1856 s. Under 10 kV/mm at 100°C, more space charge were injected into the sample than at 80°C, which extended the transient process in period I. Therefore, the transient duration (2826 s) in period III at 100°C was longer than those (1532 and 2372 s) at 80°C. However, the transient duration (2295 s) in period I under 20kV/mm at 100°C was shorter than that under 10kV/mm at 100°C, even shorter than that under 20 kV/mm at 80°C. This phenomenon was caused by that the electric field distortion after the reversal under 20 kV/mm at 100°C was the most serious as shown in Figures 6 and 7, which made the depth of the deepest trap decreased most.

According to the analysis of the preceding context, homo-charge injection appeared in the samples under dc poling field at temperatures no less than 80°C, which would distort the electric field distribution during the polarity reversal test. When the load current flowing through the low voltage DC bushing, the maximum temperature of its central conductor is generally less than 70°C. In this case, the influence of the space charge injected can be ignored in the polarity reversal test. However, in order to meet the requirement of increasing the voltage level and the current carrying capacity of UHVDC bushings in China, the bushings need to be designed to withstand higher rated voltages (\( \geq 8000 \) kV) and higher rated currents (\( \leq 6250 \) A), in which the maximum temperature may exceed 100°C. In this case, the influence of the space charge injected at high temperatures could no longer be ignored in the polarity reversal test. The distortion of electric field due to space charge at high temperatures under DC and reversal voltage should be considered in the design of the UHVDC dry bushing. These will be the focus of our future research work.

4 | CONCLUSION

In the present work, the evolutions of space charge and electric filed distribution in epoxy resin samples during the polarity reversal test have been investigated at various temperatures. It has been found that temperatures and high electric field have a significant influence on the transient process in epoxy samples during the test. Through analyzing the results, the following conclusions can be drawn:

i. At temperatures no more than 60°C, there was little space charge injected from both electrodes. A low-frequency
dielectric relaxation process was observed within the samples during the polarity reversal, which may be caused by the conductive carrier dispersion under high electric fields. The relaxation time of the low-frequency dielectric relaxation were greater than the reversal period (60s) selected in this study, which made the amount of induced charge on the electrodes after the reversal were slightly smaller than those before the reversal.

ii. At temperatures no less than 80°C, much homo-charge were injected from both electrodes in period I, III and V. The homo-charge could not be completely neutralized during the reversal and distorted the electric field distributions within the bulks of epoxy resin after the reversal. The barrier reductions under the applied electric field of 10 and 20 kV/mm were much smaller than 1 eV. Therefore, the space charge evolutions during the whole polarity
reversal test were mainly governed by a field-independent thermally activated process, and the depths of the deepest occupied traps can be obtained according to space charge decay data model proposed by Dissado.

The depths of the deepest occupied traps were about 1.13 eV at 80°C, and those were about 1.20 eV at 100°C. At temperatures no less than 80°C, the whole transient duration in period III was less than two times of transient duration in period I correspondingly.

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