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Effects of Temperature Gradient on Electrical Tree Initiation and Breakdown Phenomenon in XLPE Under Harmonic Superimposed DC Voltage

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ABSTRACT In this article, the temperature of the needle tip and the ground electrode were changed to obtain different temperature gradients. The harmonic superimposed DC voltage was also simultaneously applied to study the electrical tree initiation, growth and breakdown characteristics in cross-linked polyethylene (XLPE) under the temperature gradient. The tree inception voltage, tree structure, tree length, accumulated damage (AD) and breakdown time were used to analyze the electrical tree degradation process. It was found that the greater the temperature gradient, the easier it is for electrical trees to be initialed which is related to the different charge behaviors affected by the trap distribution indicated by surface potential decay (SPD) results at different temperatures. With the temperature gradient increasing, the electrical tree length increases firstly but then decreases slightly when the temperature of the ground electrode is fixed, but the electrical tree length and AD increase linearly with the temperature gradient increasing when the temperature of the needle tip is fixed. The temperature rise of the ground electrode has a more serious impact on the safety of the insulation compared with the temperature rise of the needle tip. Positive DC bias voltage is more likely to cause damage and breakdown than negative DC bias voltage under the temperature gradient. These results indicate that the temperature gradient and harmonic superimposed DC voltage will promote the electrical growth in cable insulation, so special attention should be paid to the safety of electrical equipment under such special conditions.

INDEX TERMS HVDC cable, XLPE, electrical tree, temperature gradient, harmonic superimposed DC voltage.

I. INTRODUCTION

HVDC cable is an effective means to solve the corridor problem of sending end, receiving end and special section, which is one of the key technologies for the development of energy internet and smart grid [1]–[3]. However, due to the existence of a large number of non-linear components such as power electronic devices in the converter bridge, and the lack of self-shut-off capability of the thyristor in the converter valve, non-characteristic harmonic voltages will be generated on the DC side in cable operation [4], [5]. The typical frequency of harmonic voltage is (2n+1) Hz, and the 1st harmonic component occupies about 18 % of DC voltage amplitude [6]. Harmonic voltage superimposed on DC voltage will produce distorted voltage waveform and threaten the stable operation of cable insulation.

Cross-linked polyethylene (XLPE) is widely used as the main insulating material for HVDC cable, and its insulation performance is inevitably affected by harmonics voltage [7]–[11]. Studies have shown that electrical trees are easier to triggered and growth under harmonic superimposed DC voltage which is an important form of polymer degradation [6]. It was found that the electrical tree growth under harmonic superimposed DC voltage also has an obvious polarity effect connected with the polarity of DC voltage [6], [12], [13].

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During the long-term operation of the cable, XLPE not only has to withstand the harmonic superimposed DC voltage, but also withstand the temperature gradient distribution. Due to the high voltage level of the DC cable, the current passing through the cable is large, resulting in a higher temperature of the insulation close to the inner conductor [14], [15]. The temperature changes with the load, which exceeds 70 °C at full load [16], [17]. Because the temperature of the insulation material close to the outside is the ambient temperature, there will be a continuous gradient temperature distribution in the insulation material. The insulation uniform conductivity, the electric field distribution and the charge transfer process will be changed by the temperature gradient, affecting the partial discharge characteristics, and thus affect the growth process of the electrical tree [18]–[21]. The influence of temperature gradient on electric field was studied, and it was found that the determined value of the maximum total electrical stress generated at the outer interface of the insulating material is mainly determined by the space charge [22]. In [23], the space charge under temperature gradient was measured and simulated, and the results showed that the distribution of space charge is determined by the balance between charge injection, migration and extraction processes, and this process is affected by temperature and electric field. The existence of the temperature gradient will cause charge accumulation near the lower temperature electrode. In [24], the initiation characteristics of the DC tree under the temperature gradient were measured, and it was found that the temperature gradient changed the initiation probability, structure, and tree length by affecting the impact ionization and electric field distribution in silicone rubber (SIR). In previous studies, we studied the initiation and growth characteristics of electrical tree under temperature gradient in SIR under repetitive pulse voltage and AC voltage, and found that the temperature gradient has great effect on the initiation and growth characteristics of electrical tree by affecting trap characteristics and charge dynamics [25], [26]. However, the research on electrical tree characteristics in XLPE under harmonic superimposed DC voltage and temperature gradient is still few.

In this paper, electrical trees in XLPE were investigated under the combination of harmonic superimposed DC voltage and temperature gradient. The experiment voltage was 14 kV harmonic superimposed ±5 kV DC voltage. The needle tip and the ground electrode temperatures were 20, 40, 60 and 80 °C, respectively. The tree inception voltage, tree structure, tree length, accumulated damage (AD) and breakdown time were used to analyze the electrical tree degradation process. The trap distribution behaviors were tested by surface potential decay (SPD) at different temperatures. The relationship between the trap distribution, the charge migration and the electrical tree degradation under harmonic superimposed DC voltage and temperature gradient were discussed based on the experimental results.

II. EXPERIMENTAL SETUP

A. SAMPLE PREPARATION

XLPE pellets (LE4253DC) supplied by Borealis Company were employed in this experiment. Experimental samples were prepared through the following steps: 1) The XLPE pellets were put in an oven at 60 °C for 24 hours to remove moisture from the raw materials. 2) The XLPE pellets were placed in the special mold which was heated to 130 °C and were held for 15 minutes to be fully melted. 3) The pressure of the tableting machine was increased and kept at 5 MPa, 10 MPa and 15 MPa for 3 minutes, respectively. 4) The pressure was reduced to 0 MPa and the set temperature was changed to 190 °C. 5) The pressure was increased to 5 MPa and 10 MPa for 3 minutes, respectively. Then it was increased to 15 MPa and kept for 30 min. 6) The sample was water cooled for 15 minutes to room temperature. 7)The prepared XLPE sample was put into a special pin mold and heated to 130 °C for 5 minutes to be soften, then a stainless steel was inserted into the sample as the needle electrode. The temperature was kept for 5 minutes, and the sample was finally water-cooled to room temperature. 8)The sample was cut into a size of 20 mm × 15 mm × 3 mm (length ×width × thickness), and the distance between the needle tip and the ground electrode was 2 ± 0.1 mm. The diameter and radius of curvature of the needle electrode were 300 μm and 3 μm, respectively.

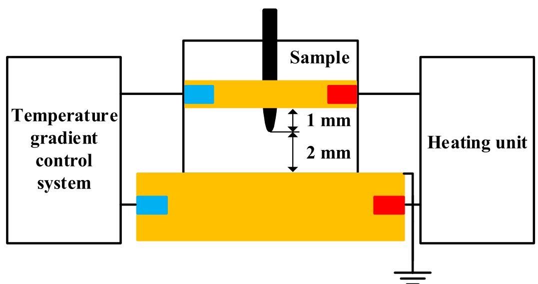

FIGURE 1. Electrical tree experimental setup.

B. ELECTRICAL TREE EXPERIMENTAL SETUP

Fig. 1 shows the electrical tree experimental setup which includes the following three parts: harmonic superimposed DC power supply, electrical tree observation system and temperature controller. DC voltage source and harmonic voltage source together constituted the harmonic superimposed DC power supply, which could generate harmonic superimposed DC voltage [6]. The DC voltage was set to ±5 kV, while the amplitude of the harmonic voltage was 14 kV and the frequency was 150 Hz. Fig. 2 shows the harmonic superimposed DC voltage waveforms. The way of pressurization was to adjust the DC voltage at the speed of 1 kV / s. After the DC voltage rose to the set value, waiting for 1 minute, and then superimposing the harmonic voltage. The XLPE sample was placed between the needle-plate electrodes. The needle electrode was used to apply the harmonic superimposed

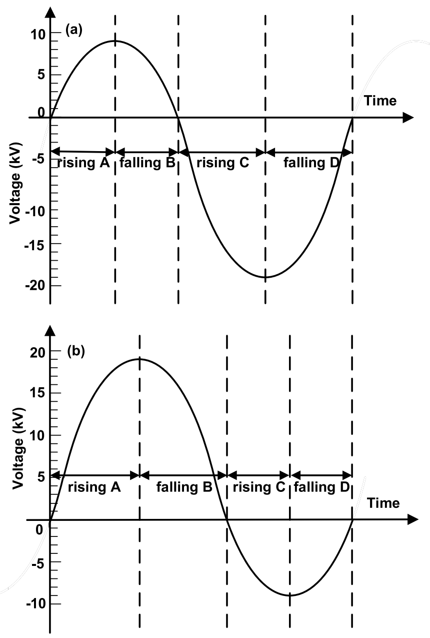

FIGURE 2. Waveforms of harmonic superimposed DC voltage.

DC voltage, and the plate ground electrode was in close contact with the bottom surface of the sample. The control range of the temperature controller (XY-WT01) was 15 to 110 °C, and the error range was ±0.1 °C. A ceramic heater was used to generate the temperature gradient between the needle tip and the ground electrode. The heating band was placed on one side of the needle electrode 1 mm above the needle tip, and the strip heater was fixed on the other side on the copper ground electrode. After each experiment, the test unit was cooled to room temperature. In the experiment, there are two types of temperature gradients: (1) The temperature of the needle tip side increases when the temperature of the ground electrode side is fixed (2) The temperature of the ground electrode side increases when the temperature of the needle tip side is fixed. ΔT represents the temperature difference between the needle tip side and the ground electrode side, as shown in the following formula:

$$\Delta T = T_N - T_G \tag{1}$$

where T_N is the temperature of the needle tip side; T_G is the temperature of the ground electrode side.

Table 1 shows different electrical tree test groups with different DC polarity and temperature gradient. The needle tip side was fixed at 20, 40, 60 and 80 °C. At each fixed needle tip side temperature, the ground electrode side temperature changed from 20 to 80 °C in steps of 20 °C. Then, the ground electrode side temperature was fixed at 20, 40, 60 and 80 °C, and the needle tip side changed in the same manner in the range of 20-80 °C. In order to ensure the accuracy of the experimental temperature, the samples were preheated for 10 minutes before each experiment. The growth characteristics of electrical tree were observed with a digital microscope. Each group tested more than 10 samples to reduce

TABLE 1. Electrical tree test groups.

Group	DC polarity	Temperature of needle tip side (°C)	Temperature of ground electrode side (°C)	Temperature gradient (°C)
1	negative	20	20	Δ0
2		40	20	Δ20
3		60	20	Δ40
4		80	20	Δ60
5		20	40	Δ-20
6		20	60	Δ-40
7		20	80	Δ-60
8	positive	20	20	Δ0
9		40	20	Δ20
10		60	20	Δ40
11		80	20	Δ60
12		20	40	Δ-20
13		20	60	Δ-40
14		20	80	Δ-60

experimental errors. As the electrical tree grew, the length and width changed with the growth time. In this paper, the tree length and AD were used to analyze the growth characteristics of electrical tree. The tree length refers to the length from the tip of the needle to the end of the electrical tree branch, which was used to analyze the growth rate of the electrical tree. The AD was used to analyze the damaged area caused by electrical tree, and the calculation method was described in the literature [27].

When testing electrical tree initiation characteristics, the DC voltage was applied to the set value at a speed of 1 kV/s firstly, and after the DC voltage rose to the set value for 1 minute, the harmonic voltage at a speed of 0.2 kV/min was applied until the electrical tree was initiated, that the tree length was longer than 20 μm. The harmonic voltage at this time was recorded as the inception voltage. Under each condition, tree inception voltages were tested for 10 times.

C. SPD MEASUREMENT

In this paper, surface potential decay (SPD) measurement method was used to calculate the trap distribution in XLPE [27]. Fig. 3 was a schematic diagram of the SPD measurement system. The sample was placed on a constant temperature heating platform, which could achieve uniform constant temperature heating of the sample. The temperature set in this paper was 20, 40 and 60 °C respectively. After the actual temperature of the preheating platform reached the set temperature, the sample was allowed to stand for 3 minutes to make the sample heated evenly. The corona power supply and the gate power supply were adjusted to the experimental voltage (needle electrode: −5 kV, gate electrode: −3 kV), and the charging time was 10 minutes. The purpose of the needle electrode and the gate electrode was to form a parallel plate electric field to charge the surface of the sample and to ensure that the surface potential of the XLPE sample was equal. The vertical distance from the needle electrode tip to the gate electrode and the vertical distance from the gate electrode to the sample surface were both 5 mm. Then turn off the corona power supply and gate power supply, and quickly move the

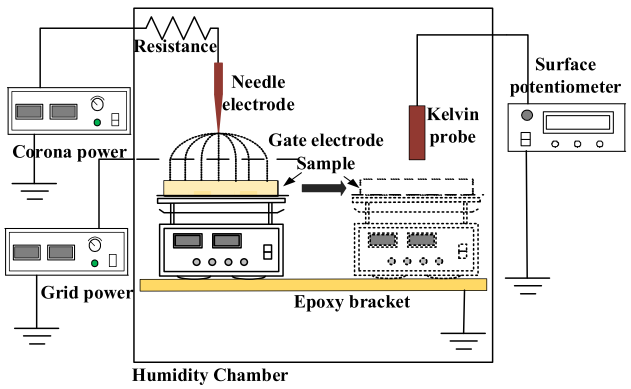

FIGURE 3. Schematic diagram of the SPD measurement system.

center of the sample below the surface potential measurement probe. The probe was located 3 mm above the center of the sample surface. The surface potentiometer and the computer were used to measure and record SPD characteristics. The relative humidity of the experiment was controlled at 20 %.

III. EXPERIMENT RESULTS

A. ELECTRICAL TREE INITIATION CHARACTERISTICS

Fig. 4 shows the tree inception voltage under the temperature gradient including data scatter. Fig. 4a shows the tree inception voltage under the temperature gradient when the ground electrode side temperature is fixed, and the data can be divided into negative DC polarity and positive DC polarity. The negative voltage indicates 14 kV harmonic superimposed −5 kV DC voltage. The positive voltage indicates 14 kV harmonic superimposed +5 kV DC voltage. With ΔT increasing from 0 to 60 °C, the mean value of inception voltage decreases from 12.33 to 8.28 kV under harmonic superimposed negative DC voltage. The mean value of inception voltage decreases from 10.90 to 8.01 kV under harmonic superimposed positive DC voltage with ΔT increasing from 0 to 60 °C. Fig. 4b shows the tree inception voltage under the temperature gradient when the needle tip side temperature is fixed, and the data can also be divided into negative DC polarity and positive DC polarity. The inception voltage has an especially obvious sharp when ΔT changes from −20 to −40 °C. Take the inception voltage change under harmonic superimposed negative DC voltage as an example: it decreases from 12.33 to 11.50 kV with ΔT changes from 0 to −20 °C, and it decreases from 8.10 to 7.63 kV with ΔT changes from −40 to −60 °C. However, it decreases from 11.50 to 8.10 kV with ΔT changes from −20 to −40 °C. It can be concluded that with the increase of ΔT, the tree inception voltage decreases. It is easier to initial an electrical tree under harmonic superimposed positive DC voltage than that under harmonic superimposed negative DC voltage.

B. ELECTRICAL TREE GROWTH CHARACTERISTICS

1) FIXED TEMPERATURE OF THE GROUND ELECTRODE SIDE

Fig. 5 shows tree structures under the temperature gradient when the ground electrode side temperature is fixed.

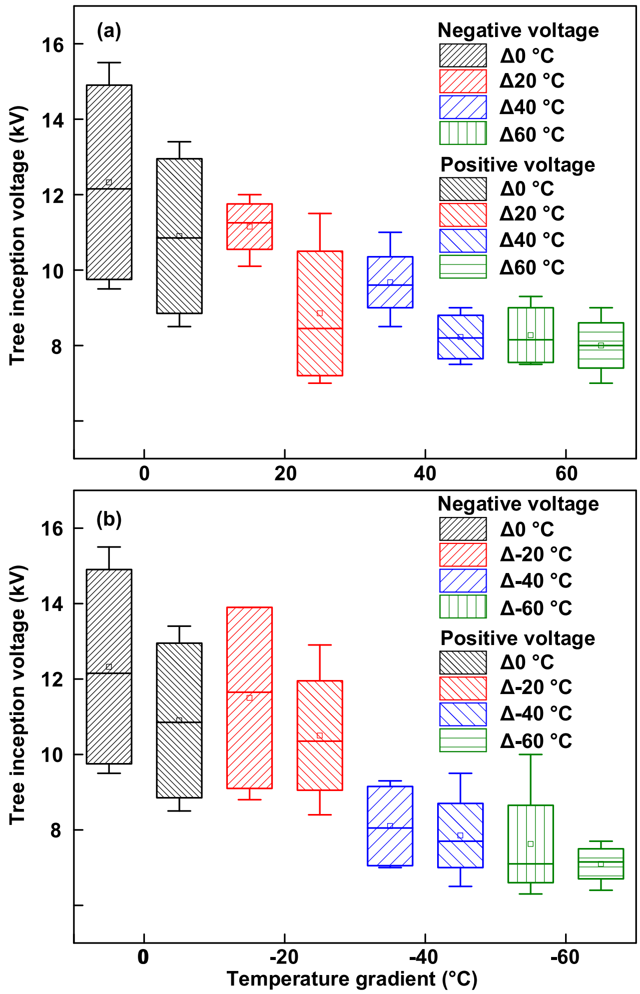

FIGURE 4. Tree inception voltage under the temperature gradient.

The treeing time is 160 s. The experiment voltage is 14 kV harmonic superimposed −5 kV DC voltage. The tree structure is bush tree around the needle tip in Fig.5a. However, with ΔT increasing from 0 to 20 °C, the tree structure changes to bush-branch tree. Bush-branch tree is a kind of double tree, the shape of which is a bush area around the needle tip, and new branch-like channels grow below the bush area when the electrical branch extends toward the ground electrode. With ΔT increasing to 40 and 60 °C, the tree structure changes to branch tree. With ΔT increasing, the darker trunks areas become bigger, and although most of them are still distributed near the needle tip, there is also a tendency to expand outward to the ground side, which is related to the severe carbon deposition caused by more inner discharges [28]. It can be seen in Fig. 5b, 5c and 5d that there are some electrical branches growing in the direction perpendicular to the electrical field near the needle tip. In Fig. 5d, some branches even grow in the direction opposite to the electrical field. As the temperature of the needle tip side increases, the partial discharge in XLPE intensifies, the local high temperature and pressure generated in internal electrical branch in a short time are more intense, the polymer molecular chain is destroyed

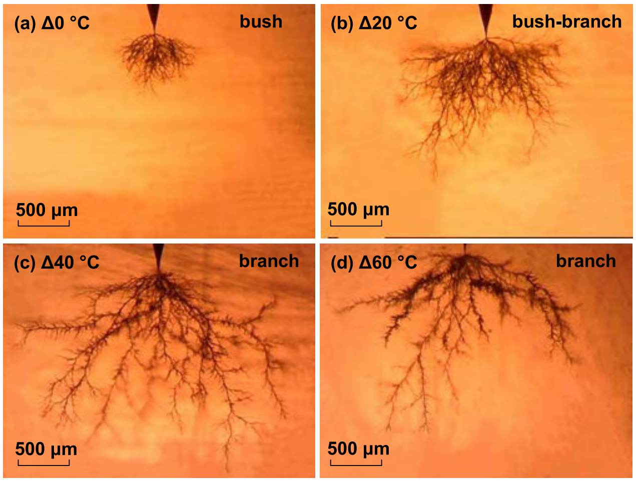

FIGURE 5. Tree structures under the temperature gradient when the ground electrode side temperature is fixed14 kV under harmonic superimposed −5 kV DC voltage.

in more random directions to create voids, and the electrical tree channels grow along the voids created in these random directions. Therefore, some branches grow in the direction perpendicular or even opposite to the electrical field.

Fig. 6 shows electrical tree growth characteristics corresponding to the tree structure in Fig. 5. Fig. 6a shows the tree length under the temperature gradient. Fig. 6b shows the corresponding AD. It can be seen in Fig. 6a that the growth rate of the electrical tree is very fast at the initiation stage at all temperatures. At $\Delta T=0$ and 20 °C, electrical tree grows at a rate lower than the initiation rate after initiation. At $\Delta T=$ 40 and 60 °C, the growth process can be divided into three stages. After fast initiation stage, there is a slower growth stage in the middle. After this second stage, the electrical tree grows at a faster rate until it breaks down. With ΔT increasing from 0 to 40 °C, the tree growth rate increases, but the growth rate at $\Delta T=60$ °C is rather special. At the early stage of electrical tree growth, the growth rate of $\Delta T=60$ °C is higher than that of $\Delta T=40$ °C, but after the electrical tree grows to about 1540 μm, the growth rate of $\Delta T=60$ °C is lower than that of $\Delta T=40$ °C. At $\Delta T=60$ °C, the electrical tree grows obviously slowly when the tree length is about 1325 μm to 1397μm. It can be seen from the corresponding electrical tree structure in Fig. 5d that the main branches near the needle tip crosses to form the darker trunks area at this stage, and it can also be seen from the corresponding AD data in Fig. 6b that the AD increases obviously at this stage. After that, although the growth rate of the electrical tree has increased at $\Delta T=60$ °C, which is still slower than that of $\Delta T=40$ °C due to the crossover of the main branches and the formation of darker trunks area. It can be concluded that with ΔT increasing, the electrical tree length increases firstly but then decreases slightly, but the AD continues to increase.

2) FIXED TEMPERATURE OF THE NEEDLE TIP SIDE

Fig. 7 shows tree structures under the temperature gradient when the needle tip side temperature is fixed. The treeing time

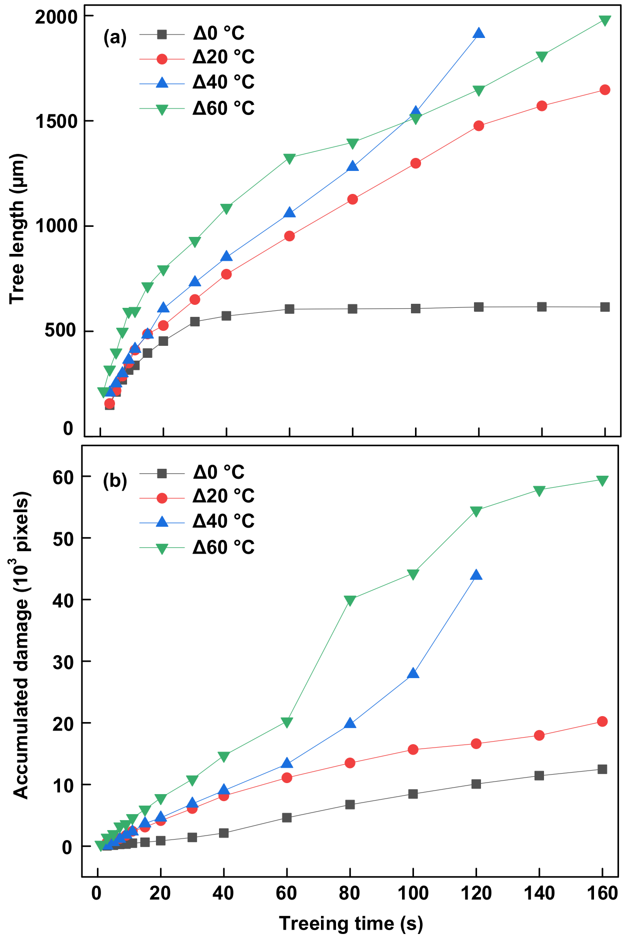

FIGURE 6. (a) Tree length and (b) AD under the temperature gradient when the ground electrode side temperature is fixed under 14 kV harmonic superimposed −5 kV DC voltage.

is 90s. The experiment voltage is 14 kV harmonic superimposed −5 kV DC voltage. It can be seen in Fig.7a and Fig.7b that the electrical tree structure is bush tree at $\Delta T=0$ and −20 °C. The tree structure is bush-branch double structure at $\Delta T=-40$°C in Fig. 7c. The tree structure changes to branch tree at $\Delta T=-60$°C in Fig. 7d. It can be concluded that with ΔTn increasing, the tree structure changes from bush tree to branch tree.

Fig. 8 shows electrical tree growth characteristics corresponding to the tree structure in Fig. 7. Fig. 8a shows the tree length under the temperature gradient. Fig. 8b shows the corresponding AD. At $\Delta T=0$ and −20 °C, the electrical tree growth rate during the initiation stage is fast, but then the electrical tree grows at a very slow rate. At $\Delta T=-40$°C, the growth rate is fast during the initiation stage and slower in the middle stage, but there is a very obvious inflection point when the electrical tree grows to 1326 μm, and then it grows at a higher growth rate which is even greater than that of the initiation stage. At $\Delta T=-60$°C, the electrical tree grows at an extremely rapid rate from initiation to breakdown. It can be concluded that with the increase of the ground electrode temperature, the growth rate of the electrical tree is accelerated.

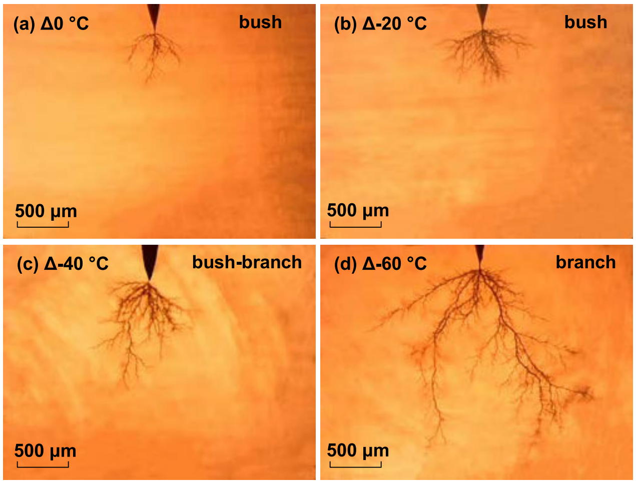

FIGURE 7. Tree structures under the temperature gradient when the needle tip side temperature is fixed under 14 kV harmonic superimposed −5 kV DC voltage.

When ΔT increases from −20 to −40°C, the growth rate increases obviously. As the temperature increases, the AD increases. But different from the changing trend of the electrical tree growth rate, the AD at ΔT= −20°C increases significantly with the increase of treeing time. This is because when the jungle-like area is formed in the bush tree, although the length of the electrical tree does not change significantly with the increase of treeing time, the branches of the electrical tree overlap each other, which increases the AD significantly.

C. ELECTRICAL TREE BREAKDOWN CHARACTERISTICS

Fig. 9 shows pre-breakdown tree structures under harmonic superimposed different polarities DC voltage under the temperature gradient when the ground electrode side temperature is fixed. At ΔT=0 °C, the electrical tree structures are bush trees under harmonic superimposed both positive and negative DC voltages. The bush area under negative DC voltage is larger than that under positive DC voltage, and the interlacing of branches is more obvious. At ΔT=20 °C, the electrical tree structures are both double trees of bush-branch types under harmonic superimposed both positive and negative DC voltages. With ΔT increasing to 40 and 60 °C, the electrical tree structures are all branch trees. It can be concluded that as ΔT increases under the temperature gradient when the ground electrode side temperature is fixed, the electrical tree structure changes from dense bush tree to sparse branch tree under harmonic superimposed both positive and negative DC voltages. At the same ΔT, the number of main branches and side branches of the electrical tree under harmonic superimposed negative DC voltage is greater than that under harmonic superimposed positive DC voltage, and the overall lateral extension of the electrical tree is wider under harmonic superimposed negative DC voltage. The width of the branch channel is also wider under harmonic superimposed negative DC voltage than that under harmonic superimposed positive DC voltage, which is especially obvious at ΔT=60 °C.

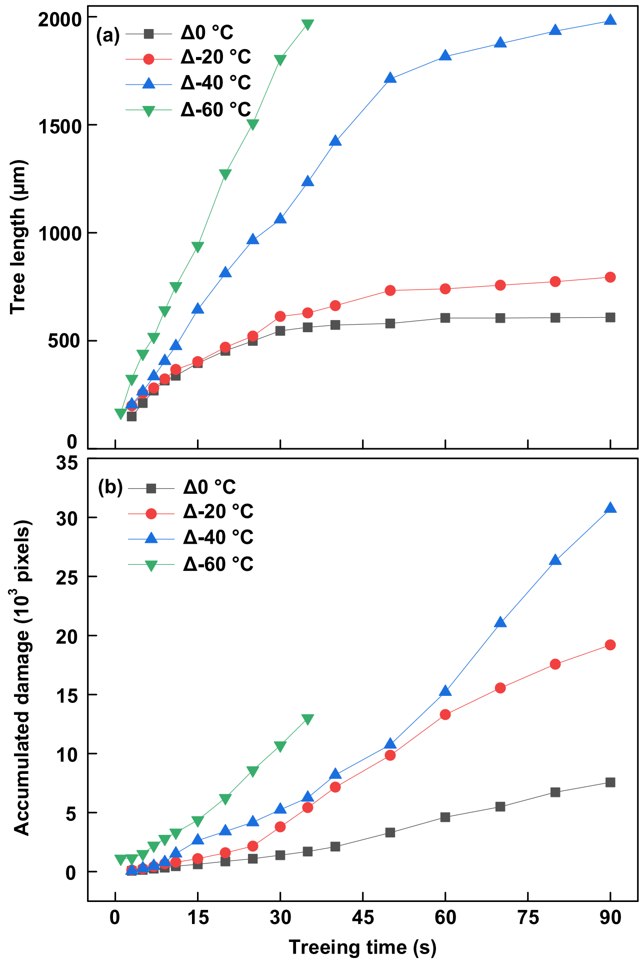

FIGURE 8. (a) Tree length and (b) AD under the temperature gradient when the needle tip side temperature is fixed under 14 kV harmonic superimposed −5 kV DC voltage.

Fig. 10 shows pre-breakdown tree structures under harmonic superimposed different polarities DC voltage under the temperature gradient when the needle tip side temperature is fixed. At ΔT= −20°C, the electrical tree structures are both bush trees under harmonic superimposed both positive and negative DC voltages, which are similar conditions as the tree structures at ΔT= 0°C (as shown in Figure 9 (a1) and 9(a2)). At ΔT= −40°C, the tree structure is branch tree under harmonic superimposed positive DC voltage, but the tree structure is a double tree of bush-branch type under harmonic superimposed negative DC voltage. At ΔT= −60°C, the electrical tree no longer exists in the bush area under harmonic superimposed both positive and negative DC voltages, and the tree structures are branch trees. It can be summarized that no matter under harmonic superimposed the positive voltage or the negative voltage, with the increase of ΔT, the electrical tree structure changes from bush tree to sparse branch tree under the temperature gradient when the needle tip side temperature is fixed, which is the same as the conclusion when the ground electrode side temperature is fixed. At the same ΔT, the number of branches of the electrical tree under harmonic superimposed negative DC voltage is greater

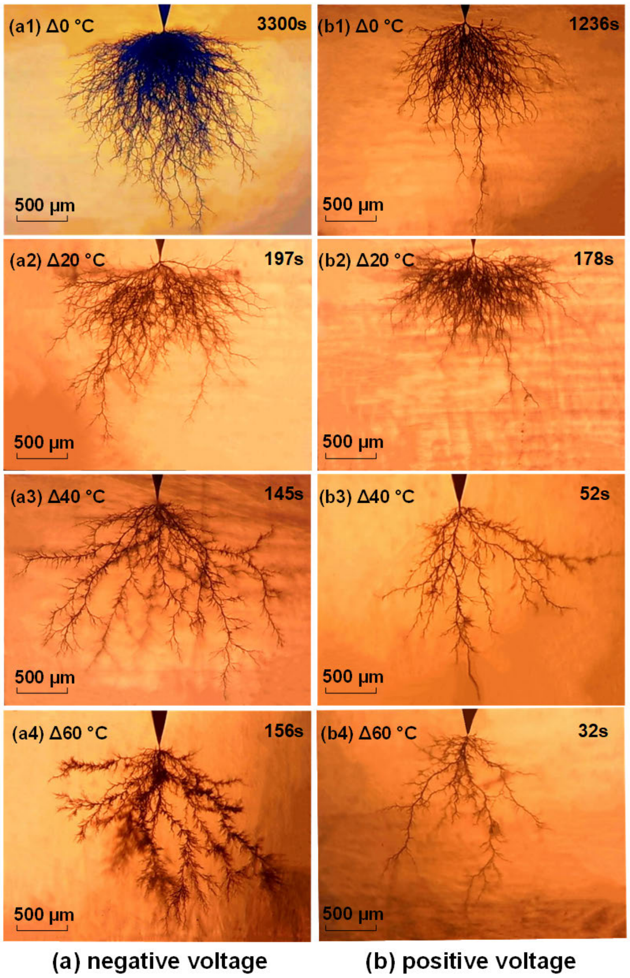

FIGURE 9. Pre-breakdown tree structures under harmonic superimposed different polarities DC voltage under the temperature gradient when the ground electrode side temperature is fixed.

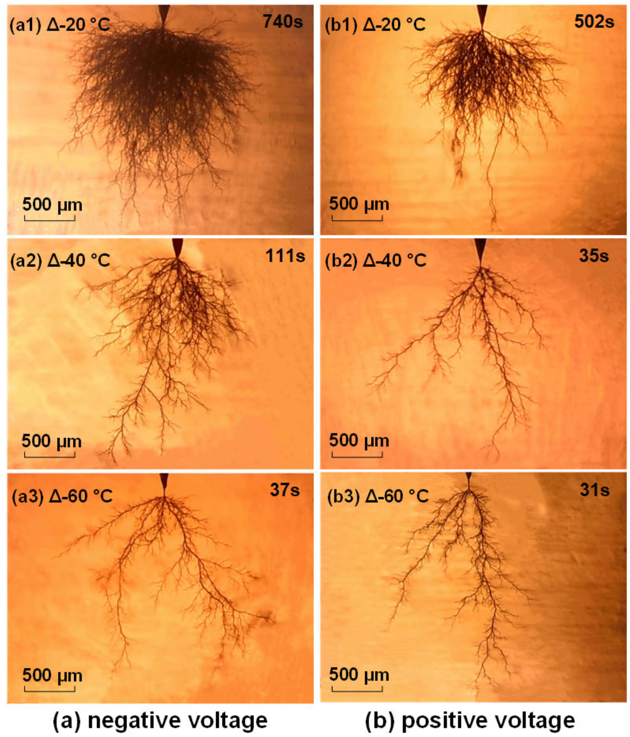

FIGURE 10. Pre-breakdown tree structures under harmonic superimposed different polarities DC voltage under the temperature gradient when the needle tip side temperature is fixed.

than that under harmonic superimposed positive DC voltage, which is also the same as the conclusion when the ground electrode side temperature is fixed.

Fig. 11 shows the electrical tree breakdown time under the temperature gradient including data scatter. Figure 11a shows the electrical tree breakdown time when the ground electrode side temperature is fixed. Under harmonic superimposed positive DC voltage, as ΔT increases from 0 to 60 °C, the breakdown time decreases significantly from 1037 to 33 s (average value), and the gap between 0 and 20 °C is particularly significant, from 1037 to 159 s. Under harmonic superimposed negative DC voltage, when ΔT rises from 0 to 20 °C, the breakdown time decreases significantly from 3045 to 215 s, and with ΔT rises from 20 to 40 °C, the breakdown time decreases from 215 to 141 s, which is the same as that under harmonic superimposed positive DC voltage. But the difference is that the breakdown time of ΔT=80 °C is 142 s, which is not much different from ΔT=60 °C, and even longer than that of ΔT=60 °C under harmonic superimposed negative DC voltage. Figure 11b shows the electrical tree breakdown time when the needle tip side temperature is fixed. As ΔT increases from 0 to 60 °C, the electrical tree breakdown time drops sharply regardless of whether the polarity of DC voltage is positive or negative. Even at ΔT=60 °C, the average electrical tree breakdown time is less than 40 s. It can be concluded that ΔT has a nonlinear effect on the breakdown time of electrical tree. The temperature rise of the ground electrode has a more serious impact on the safety of the insulation. DC voltage polarity also has a certain effect on the breakdown time of the electrical tree. The breakdown time under harmonic superimposed positive DC voltage is significantly shorter than that under harmonic superimposed negative DC voltage. As shown in Fig. 11a, the breakdown time gap between positive and negative DC polarities is large under the temperature gradient when the ground electrode side temperature is fixed. Under the temperature gradient when the needle tip side temperature is fixed, at ΔT=0, −20 and −40 °C, the breakdown time difference between positive and negative DC polarities is very large, but at ΔT= −60°C, the breakdown time difference between positive and negative DC polarities is not large, because the electrical tree grows very fast at this time, and breakdown occurs quickly under both positive and negative DC polarities. According to the above results, it can be concluded that the insulation material is more easily damaged under the temperature gradient. In most cases, the greater the temperature gradient, the faster the insulation is destroyed. Positive DC bias voltage is more likely to cause insulation damage and breakdown than negative DC bias voltage.

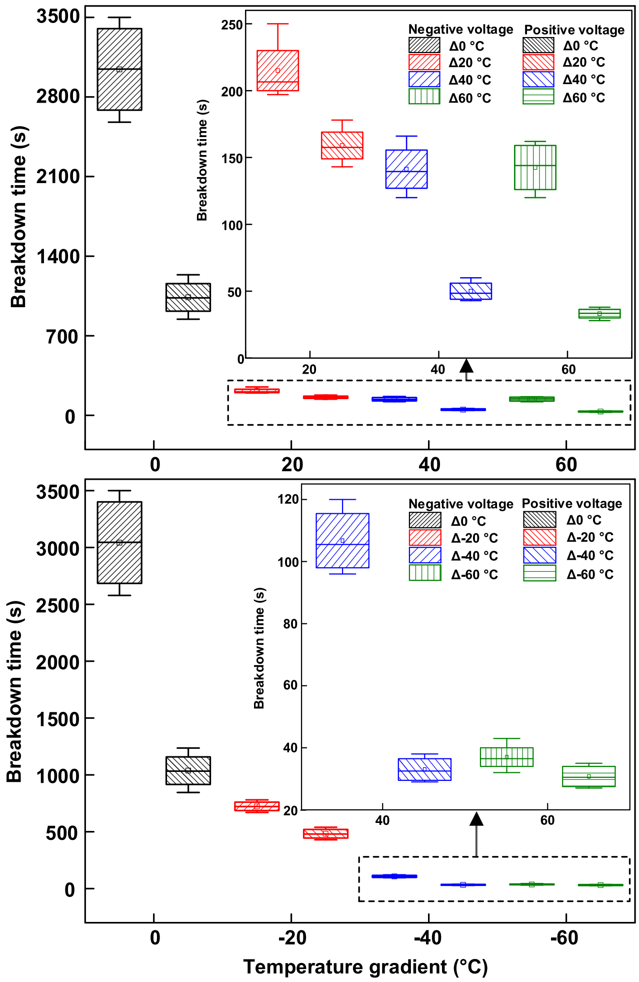

FIGURE 11. The electrical tree breakdown time under the temperature gradient. (a) the ground electrode side temperature is fixed; (b) the needle tip side temperature is fixed.

IV. DISCUSSION

A. ELECTRICAL TREE INITIATION

The needle-plate system is a typical distortion electric field after the voltage is applied. When the local electric field strength exceeds the relevant critical field of the insulation, the charge carriers will enter a state of high mobility [29]. Then, charges are passed through the interface of the needle and the dielectric, and are injected into the polymer by the needle tip, after which they may continue to move or fall into traps, which form the space charge together with other charges formed by partial discharge or ionization [30], [31]. Homogenous space charges accumulate near the tip, thereby reducing the electric field near the tip [32]. The charge injection will stop when the local electric field is equal to the critical electric field of the insulation. When the DC component voltage is applied at first, electrons are passed through the barrier on the metal-polymer interface, and are trapped near the needle tip under 14 kV harmonic superimposed −5 kV DC voltage. After the harmonic superimposed DC voltage is generated, in the positive voltage rising stage (corresponding to stage rising A in Fig. 2(a)), a large amount of positive charges is injected instantaneously from the needle tip. On the one hand, positive and negative charges are neutralized to release energy. On the other hand, positive charges that are not neutralized with negative charges will fall into traps. In the positive voltage falling stage (corresponding to stage falling B in Fig. 2(a)), when the superimposed voltage drops, some of the positive charges closer to the needle tip will escape the trap and move to the needle electrode, while other charges far away from the needle tip will still be trapped due to insufficient local electric field. In the negative voltage rising stage (corresponding to stage rising C in Fig. 2(a)), negative charges are injected, part of the negative charges is neutralized with positive charges, and part of the negative charges is trapped. In the negative voltage falling stage (corresponding to stage falling D in Fig. 2(a)), some negative charges are removed from traps by the electric field and move to the needle electrode, while other negative charges are still captured by traps. During the periodic rise and fall of the voltage, charges will repeat these migration processes due to changes in the electric field. In this process, both the charge trapping and the neutralization of the positive and negative charges will generate energy, by which the polymer is decomposed into free radicals to form the low-density zone. Impact ionization occurs in the low-density zone, destroying more molecular chains and forming micropores. The generated free radicals and broken molecular chains will also generate more traps and accelerate the formation of degraded areas. After partial discharges occur, the local temperature rises and a large amount of gas will be generated in a short time, causing micropores to expand rapidly to the amorphous, initiating the electrical tree [33]. When the applied voltage is 14 kV harmonic superimposed +5 kV DC voltage, the mechanism of electrical tree initiation is similar to that of harmonic superposition −5 kV DC voltage, except that the charge migration process is different. When the DC component voltage is applied, positive charges are injected by the needle tip, and are trapped near the needle tip. After the harmonic superimposed DC voltage is generated, in the positive voltage rising stage (corresponding to stage rising A in Fig. 2(b)), a large amount of positive charges is injected from the needle tip instantaneously, and these charges stimulate the trapped charge to detrap, and part of the injected charges will be trapped around the needle tip after one or more scattering, reducing the electric field strength and electron injection rate in these places. In the positive voltage falling stage (corresponding to stage falling B in Fig. 2(b)), part of positive charges will escape the traps and move back to the needle electrode, and part of positive charges will still be captured by the traps. In the negative voltage rising stage (corresponding to stage rising C in Fig. 2(b)), negative charges are injected. Part of the negative charges and positive charges are neutralized to generate energy, and part of the negative charges is trapped. In the negative voltage falling stage (corresponding to stage falling D in Fig. 2(b)), some negative charges are escaped from the traps by the electric field and move to the needle electrode, while other negative charges are still captured by the traps. The different electrical tree inception voltage under different DC voltage polarities are caused by the different properties of charge carriers. Since electrons have the characteristics of small mass and high mobility, they are easier to inject into the polymer than positive charges. A large number of injected electrons will shield the high electric field at the needle tip, reducing the charge injection rate, leading to lower tree inception voltage under harmonic superimposed positive DC voltage [34], [35].

Fig. 12 shows the trap distribution behaviors in XLPE at 20, 40 and 60 °C. As the temperature increases, the peak trap density of shallow traps becomes larger, and the peak trap density of deep traps becomes smaller. As the temperature increases, the energy level in deep traps and shallow traps increases. High temperature affects the thermal excitation of the charge, and the excited charge is more likely to be separated from the trapping center. Unless it is captured again, the mobile charge will be transferred to the opposite electrode. From this, it can be seen that charges are difficult to escape after trapped in the low temperature region, only small part of which can escape from the shallow trap. As the temperature increases, charges are more easily detrapped. In the high temperature region, excited charges are easier to detrap and migrate in the polymer. The cyclically varying electric field results in repeated charge trapping and detrapping processes under harmonic superimposed DC voltage. Therefore, as ΔT increases, more charges are excited, resulting in lower tree inception voltage.

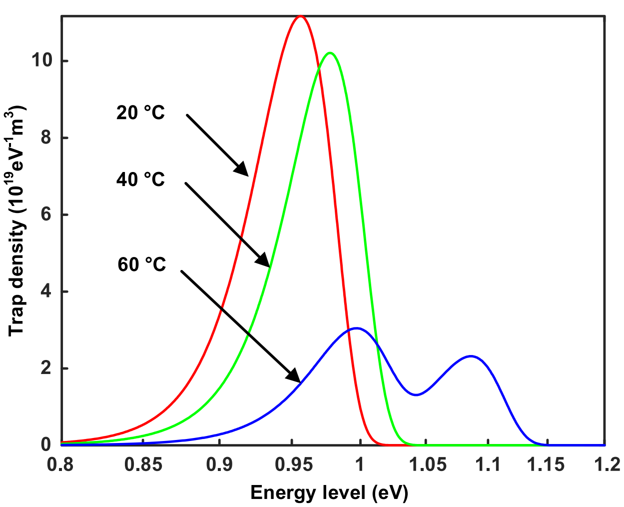

FIGURE 12. Trap distribution behaviors of different temperatures in XLPE.

B. ELECTRICAL TREE GROWTH AND BREAKDOWN

In the case when the ground electrode side temperature is fixed, the rising temperature in needle tip will affect the amount of injected charges. As the temperature of the needle tip side increases, the amount of injected charge increases [36]. The excited charge is also easier to detrap, and is easier to move in the polymer matrix, promoting the growth of electrical tree. Therefore, as the temperature of needle tip side increases from 20 to 60 °C, the electrical tree growth rate and the AD increase. Under negative DC bias voltage, when the needle tip temperature increases from 60 to 80 °C, it can be seen in Fig. 6 that before the electrical tree grows to 1540 μm, the electrical tree length of 80 °C is longer than that of 60 °C, but after that, the electrical tree length of 80 °C is shorter than that of 60 °C. And it can also be seen from Fig. 11 that there is no big difference between the breakdown time of 60 and 80 °C. The increase of the needle tip side temperature from 60 to 80 °C does not lead to an increase in the growth rate, but reduces the growth rate when the electrical tree grows near to the ground electrode. This is because, on the one hand, as the temperature changes, the relative permittivity ε_r changes very little, but the electrical conductivity changes significantly. Since the electric field distribution is mainly affected by the conductivity, compared to room temperature, the electric field on the high temperature side decreases while the electric field on the low temperature side increases under the needle-plate system. When the temperature changes from 60 to 80 °C, the conductivity has a significant increase [36], so the electric field at the needle tip will be reduced by the excessive temperature. On the other, when the ground electrode temperature is fixed, charges are injected from the high temperature region around the needle tip and transferred inside the XLPE, and finally falls into the traps in the low temperature region around the ground electrode. Because of the decrease of temperature and electric field, the trapped charges are difficult to escape, and the charges are easier to accumulate around the ground electrode. Under the negative DC bias voltage, the number of injected and moved electrons is large, and the electrons are trapped near the ground electrode and accumulate as space charges, shielding the electric field, which causes the growth rate of electrical tree at 80 °C to decrease instead. It can be seen in Fig. 11 that under the positive DC bias voltage, the breakdown time of 80 °C is less than that of 60 °C. This is because electrons have higher mobility than positive charges and are easier to be trapped. Under the positive DC bias voltage, the shielding effect of space charge is not obvious, and the main effect is the effect of temperature on the increase of charge mobility and detrapping rate.

When the needle tip side temperature is fixed, the electric field of the needle tip increases compared with the temperature of the ground electrode due to the effect of conductivity. After charges are injected into XLPE, some of them are trapped, while other charges escape from the shallow trap and migrate to the ground electrode. Due to the temperature gradient distribution, charge carriers migrate from the low temperature region to the high temperature region. When the ground electrode temperature is low as 20 and 40 °C, more charges will trap around the main channels of the electrical tree, forming a space charge shielding layer, which makes the electrical tree easier to form a bush area, which explains the formation of bush tree in Fig. 9 (a1), 9(b1), 10 (a1) and 10 (b1). Since electrons are more easily trapped than positive charges, even if the temperature of the ground electrode rises to 60 °C, the double tree structure under negative DC bias voltage still has a bush area (as shown in Fig.10 (a2)). As the temperature of the ground electrode rises to 80 °C, because the kinetic energy of the charge is higher, more charges escape from the traps. The thermal charge is difficult to be captured at high temperature, so under the influence of high temperature, there is less charge accumulated around the tree channel, and the shielding effect is not obvious. The structure of the electrical tree is a branch tree when the temperature of the ground electrode side is 80 °C. The effect of high temperature promotes the transfer of charges. Therefore, when the ground electrode side temperature increases, the electrical tree grows faster and the AD is greater.

V. CONCLUSION

In this study, electrical tree initiation, growth and breakdown characteristics were investigated under harmonic superimposed DC voltage and the temperature gradient. The trap distribution behaviors of different temperatures were tested by SPD. The electrical tree characteristics affected by harmonic superimposed DC voltage and temperature gradient were discussed. The conclusions could be summarized:

1) With the increase of ΔT, the tree inception voltage decreases which is related to the different charge behaviors affected by the trap distribution at different temperatures. The greater the temperature gradient, the easier it is for electrical trees to be initialed.

2) When the ground electrode side temperature is fixed, with ΔT increasing, the electrical tree length increases firstly but then decreases slightly, but the AD increases linearly. When the needle tip side temperature is fixed, with the ΔT increasing, the electrical tree length and AD increase linearly. These differences are caused by different conductivity, electric field, charge migration, and space charge distribution under different temperature gradients.

3) ΔT has a nonlinear effect on the breakdown time of electrical tree. The greater the temperature gradient, the faster the insulation is destroyed in most cases. The temperature rise of the ground electrode side has a more serious impact on the safety of the insulation compared with the temperature rise of the needle tip side.

4) The initiation, growth and breakdown characteristics of electrical tree under harmonic superimposed DC voltage all have polarity effects. Positive DC bias voltage is more likely to cause damage and breakdown than negative DC bias voltage under the temperature gradient which is related to the different characteristics between electrons and holes.

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