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Electrical Tree Growth Characteristics in Epoxy Resin With Harmonic Superimposed DC Voltage

BOXUE DU, (Senior Member, IEEE), MENG TIAN, JINGANG SU, AND TAO HAN, (Member, IEEE)

Key Laboratory of Smart Grid of Education Ministry, School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China

Corresponding author: Tao Han (hant@tju.edu.cn)

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ABSTRACT HVDC converters can generate harmonic voltage, which distorts the DC voltage quality and threatens epoxy resin insulation reliability. In this paper, the electrical tree growth was investigated in epoxy resin under harmonic superimposed DC voltage. The DC voltage ranged from −20 to +20 kV and harmonic frequency ranged from 50 to 450 Hz. This experiment was carried out with needle-plate electrodes system. The effects of DC amplitude and harmonic order were characterized by electrical tree length and accumulated damage. Results show that the electrical tree varies with different combinations of DC amplitudes and harmonic orders. The tree length and accumulated damage experience a non-linear trend with the rise of harmonic order. The low-order harmonics bring more damage to epoxy resin under superimposed voltage. The time to breakdown shows a minimum value at 3rd harmonic superimposed voltage. The DC amplitude has an acceleration on the electrical treeing process. With higher DC amplitude, the electrical tree breakdown happens immediately when the electrical tree reaches the plate electrode. The charge transport process accounts for the tree initiation characteristics under different superimposed DC amplitudes and harmonic orders. Meanwhile, "reverse tree" has been found in epoxy resin sample. The field-driven tree growth model has been employed to interpret reverse tree growth from the perspective of dynamic electric field distribution.

INDEX TERMS Epoxy resin, HVDC converter, superimposed voltage, electrical tree, dielectric breakdown, accumulated damage.

I. INTRODUCTION

Epoxy resin has superior electrical performance and outstanding mechanical property. Therefore, it is widely used in high-voltage direct current (HVDC) power equipment insulation such as bushing, termination [1], [2]. However, insulation breakdown failure constantly happens in HVDC equipment insulation [3]. A non-negligible factor is the existence of harmonic contents, which is caused by the rectification of AC waveform in HVDC converters [4], [5]. According to the actual operating voltage waveform in converter transformer, the 1st harmonic voltage accounts for 18.5% of the DC voltage content after the Fourier decomposition [6]. The complicated superimposed voltage brings great threat to epoxy resin insulation. Literature [7] studied the impact of harmonics on the polymer breakdown through electrical treeing process. The harmonic voltage can cause the electrical tree, and eventually leads to breakdown. Understanding the degradation mechanism of epoxy resin under harmonic superimposed DC voltage is important to power grid safety.

The polymer degradation mechanism is relevant to microscopic charge transport and trapping process, which depends on the property of charge carriers [8], [9]. Many literatures have studied the charge transport process during the electrical treeing process. In [10], the charge carriers are found to be injected via high divergent field and accumulated around the needle tip. The homo space charges moderate the electric field around the needle tip, it explains why it is hard to initiate tree under DC voltage even up to 70 kV [11]. On the other hand, the tree generation is determined by the charges that can quickly transport back to the electrode under DC grounding voltage [12]. In [13], a charge distortion model was

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proposed for the electrical tree initiation mechanism under AC voltage. The injected charge carriers moved back and forth periodically between the polymer and electrode. The repeated process of charge injection and extraction accounts for tree initiation as well as material aging. In [14], the repetitive charge injection process becomes more frequent with the increase of pulse frequency. Numerous charges collide with the insulation polymer and break the molecular chains, forming degradation zone and leading to electrical tree.

Under superimposed voltage, the charge transport process becomes more complicated. In [15], the bias negative DC voltage injects electrons by field emission. After the pulse voltage is superimposed on DC voltage, the combined DC-pulse voltage will be generated. With the same polarity pulse voltage, some hot electrons get sufficient energy due to the enhanced electric field. Meanwhile, the trapped charges gain enough energy to detrap [16]. With the opposite polarity pulse voltage, the different charge transport processes will happen depending on the zero-cross point of combined voltage. Conclusion can be drawn that the charge transport is closely correlated with applied voltage waveform [11]–[15]. Therefore, the harmonic superimposed DC voltage can cause different charge transport processes and induce electrical tree. Unfortunately, research on the effect of harmonic superimposed DC voltage on electrical tree and polymer degradation is not enough.

In this paper, electrical treeing test was performed in the needle-plate system to simulate the metallic asperities or protrusions on a real conductor. Treeing process has been investigated with the application of harmonic superimposed DC voltage. With the numerous combinations of DC amplitudes and harmonic orders, different superimposed voltages are stressed on epoxy resin samples. The accumulated damage is used as a supplementary measurement to electrical tree length. The charge transport processes account for the different tree initiation characteristics. Moreover, the reverse tree growth is found in this experiment and is interpreted by dynamic divergent electric field distribution.

II. EXPERIMENTAL ARRANGEMENT

The epoxy HY-511 and amine harder HY-651 are provided by Yanhai-Resin. A magnetic stirrer was employed to mix the epoxy and the amine hardener uniformly on the scale of 3 to 1 [16]. In order to remove the gas in the mixture, the liquid mixture was degassed sufficiently in a vacuum chamber at 25 °C. Then the mixture was moved into a stainless steel mold, and the metal needle was pre-embedded for electrical tree experiment. The metal needle had a tip curvature radius of 3 μm and a tip angle of 30 degree. The insulation thickness from needle tip to bottom of sample was 2 ± 0.1 mm, which constituted the needle-plate electrode system. The plate electrode was well grounded by attaching copper foil to the bottom of the sample. The sample was manufactured into epoxy slabs with 15 mm × 20 mm × 4 mm in dimension. The epoxy slabs were pre-cured at room temperature (∼ 25°C) for 48 h and post-cured at 60 °C for 8 h to ensure complete curing reaction. To verify the geometry of electrode system, the samples were controlled within permissive range in needle-plate distance and no void around the needle tip, which was selected by microscope.

The testing system mainly consisted of a voltage-coupling unit, a test cell and a digital microscope imaging system [15]. The DC source output and harmonic source output can be integrated into the harmonic superimposed DC voltage by voltage-coupling unit. The DC amplitudes were set to 0, ±10 and ±20 kV. The frequencies of harmonic voltage were set to 50, 150, 250, 350 and 450 Hz and the peak amplitude was set to 15 kV. During the experiment, the DC voltage was applied with a rising speed of 1 kV/s at first. Then the harmonic voltage was applied 1 min later to generate the harmonic superimposed DC voltage. The sample was stressed with superimposed voltage in test cell and immersed in silicone oil to prevent the flashover. Once the superimposed voltage was stressed on the sample, the silicone oil would slosh due to the electrophoretic effect, which is different from harmonic treeing experiment. It is difficult to carry out real-time observation, and hence the samples were observed under the digital microscope when the superimposed voltage was removed and naturally decayed to zero. More than 10 samples have been tested on each condition of superimposed voltage to ensure the veracity of tree initiation experiments.

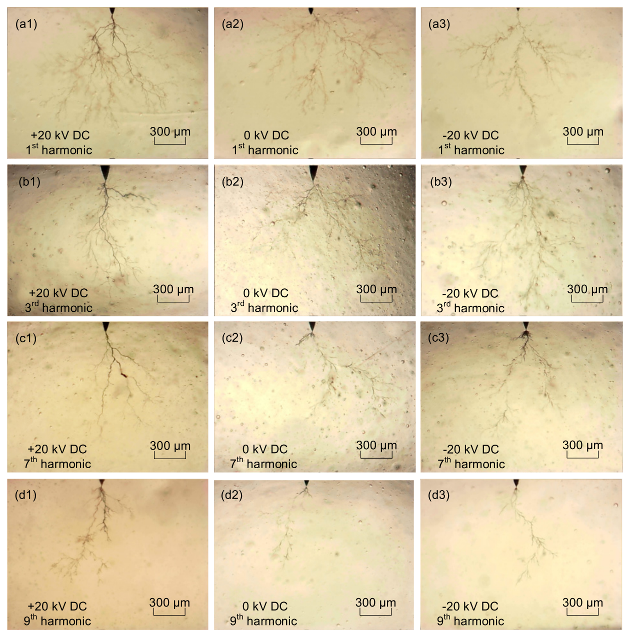

FIGURE 1. Typical electrical tree under different harmonic superimposed DC voltages for 15min.

III. RESULTS

A. HARMONICS ORDER SUPERIMPOSED DC VOLTAGE

Fig. 1 shows the typical tree structure under different superimposed voltages. The basic tree shape is branch structure under all kinds of superimposed voltages. There are still some differences in electrical tree morphology with the varying harmonic superimposed DC voltage. When the DC component is +20 kV, the main branch channel is in dark color with filamentous branches propagating from it. While the filamentous side branches decrease significantly with the rise of harmonic order. It can be found that the filamentous bifurcation decreases with the increase of harmonic order under harmonic voltage or other superimposed voltages.

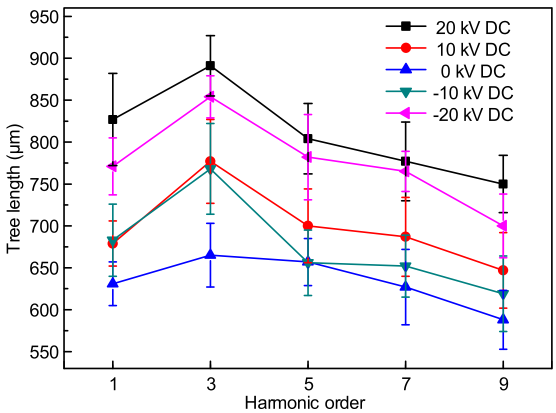

FIGURE 2. Relation between the tree length and harmonic order under different harmonic superimposed DC voltages for 10 min.

Fig. 2 shows the relation between the electrical tree length and harmonic order under different superimposed voltages for 10 min. The electrical tree length describes the furthest distance between the needle tip and tree tip along the vertical direction. Under different harmonic orders, the tree length increases with DC amplitude. With the increase of harmonic order, the tree length shows a non-linear trend, for it increases at first and then decreases under harmonic voltage. It reaches a maximum length at 3rd harmonic voltage. With the increase of DC amplitude, it becomes more obvious that maximum length occurs under 3rd harmonic superimposed DC voltage.

In electrical treeing process, the electrical tree propagates in both vertical and horizontal direction, and the accumulated damage is a parameter to assess the holistic damage degree caused by tree growth as a supplement. It is calculated according to the damage region occupied by electrical tree channel in pixels, more details can be found in [14]. To conduct a further investigation on tree characteristics, Fig. 3 shows the relation between accumulated damage and harmonic order under different superimposed voltages for 10 min. Fig. 3 illustrates a downward trend with the rising of harmonic order at the same treeing time. The maximum damage is for 1st harmonic and it is caused by the numerous filamentous branches. Comparing with other harmonic superimposed DC voltages, the harmonic voltage shows a sharper decline in tree length with increasing harmonic order. Fig. 3 indicates that the low-order harmonics cause more damage on epoxy resin under superimposed voltages, and more attentions should be paid to low-order harmonics during the operation of power equipment.

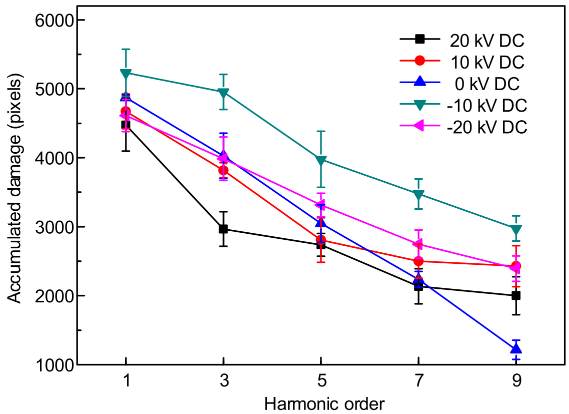

FIGURE 3. Relation between the accumulated damage and harmonic order under different harmonic superimposed DC voltages for 10 min.

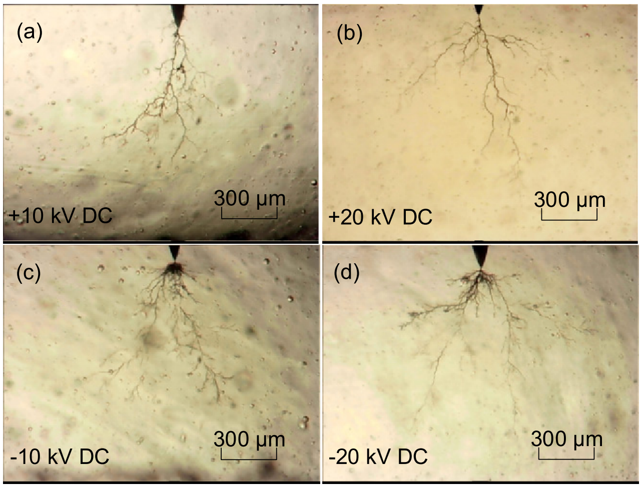

FIGURE 4. Typical electrical tree under 5th harmonic superimposed DC voltage for 15min.

B. HARMONIC ORDER SUPERIMPOSED DC AMPLITUDE

Fig. 4 shows the typical tree structure under 5th harmonic superimposed DC voltage, where the harmonic amplitude is 15 kV and treeing time is 15 min. When the harmonic voltage is superimposed with positive DC voltage, the main branch channel is dark and easily to be observed (shown in Fig. 4a). Many filamentous branches are generated from the main channel with relatively lighter color. With the increase of positive DC amplitude, the filamentous branches decrease in number and get longer in length (shown in Fig. 4b). As for the harmonic superimposed negative DC voltage, the electrical tree near the needle tip is dark and have a trend to be bush-like (shown in Fig. 4c). With the increase of negative DC amplitude, the light filamentous branches show the same trend that decreases in number and elongates in length (shown in Fig. 4d). It is notable that intense discharge and oxidation can lead to chemical decomposition depositing in the tree channel, and hence the initial light branch can turn into darker branch or dense bush with the feature of semi-conducting [17]. The dark tree channel and slender filamentous branches indicate that more intense discharges happen with the existence of DC components. This can be interpreted as the DC component rises the electric field near the needle tip and leads to more intense and severe discharges.

For a further understanding of electrical treeing process under superimposed voltages, the relation between the tree length and different superimposed voltages has been plotted in Fig. 5. The electrical tree under 5th harmonic voltage has been used as a control. It takes the longest time for harmonic tree to reach the ground electrode. With the increase of DC amplitude, the electrical tree propagates faster, which is in accord with the tree length in Fig. 2. The DC polarity has an evident effect on electrical tree propagation, for the tree growth rate in positive DC superimposed voltage is higher than that in negative DC superimposed voltage. In late stage of tree growth, the DC component has a more apparent accelerating effect for the tree tips are near to the ground electrode.

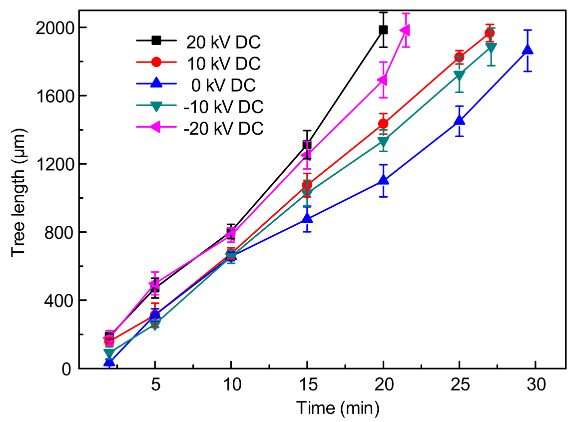

FIGURE 5. Electrical tree length under different harmonic superimposed DC voltages with 5th harmonic.

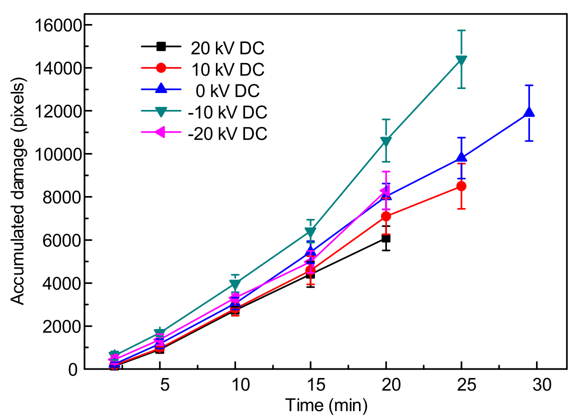

FIGURE 6. Accumulated damage under different harmonic superimposed DC voltages with 5th harmonic.

The relation between the accumulated damage and different superimposed voltages has been shown in Fig. 6, which is consistent with the results in Fig. 3. With the increase of treeing time, the differences between the superimposed voltages become more obvious. Comparing with the 5th harmonic voltage, the negative DC superimposed voltages seem to cause greater damage to the epoxy resin. The positive DC component causes a lower damage degree than the negative DC component under superimposed voltage, it can be explained that bush-like tree causes larger damage area than branch-like tree. The effect of DC voltage on electrical tree under superimposed voltages can be depicted as follows. The DC component can intensify the discharge within the tree channel, and hence the electrical tree tends to propagate toward the ground electrode and the main channel turns into dark color. The number of filamentous branches decreases for more intense discharges in higher DC amplitude.

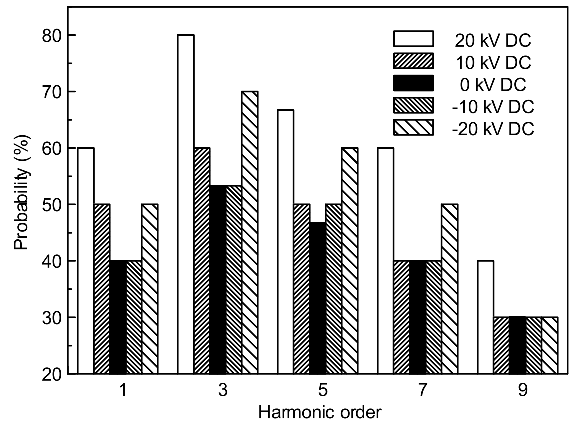

FIGURE 7. Relation between the inception probability and the harmonic order under different harmonic superimposed DC voltages.

The relation between the probability of tree initiation and different superimposed voltages has been shown in Fig. 7, which can provide a deeper understanding to the effects of harmonic order and DC amplitude under superimposed voltages. There is an incubation stage before electrical tree can be recognized by microscope, an electrical tree is defined when the tree length is longer than 30 μm in 2 min [18]. When the DC voltage is superimposed on harmonic voltage, the tree initiation probability increases to different extent, especially for harmonic superimposed +20 kV DC voltage. It can be seen that the positive DC component has a more obvious acceleration than the negative DC component on electrical tree initiation. With the increase of harmonic order, the initiation probability shows a non-linear trend, for it increases at first and then decreases. It reaches a maximum value at 3rd harmonic superimposed DC voltage, which is same with the non-linear trend found in tree length (shown in Fig. 2). Distinct charge transport process happens, so differences in tree initiation characteristics exist under harmonic superimposed DC voltages. The property of injected charge carrier accounts for the differences in DC voltage polarity and harmonic order, and it will be discussed in Section 4.1.

C. DIELECTRIC BREAKDOWN AND REVERSE TREE

Dielectric breakdown is the most noteworthy phenomenon that is closely linked to insulation security operation. In Fig. 8, the time to breakdown has been counted.

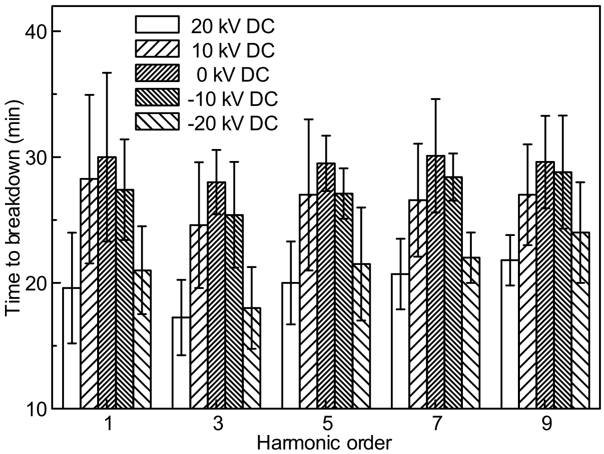

FIGURE 8. Time to ground electrode under different harmonic superimposed DC voltages.

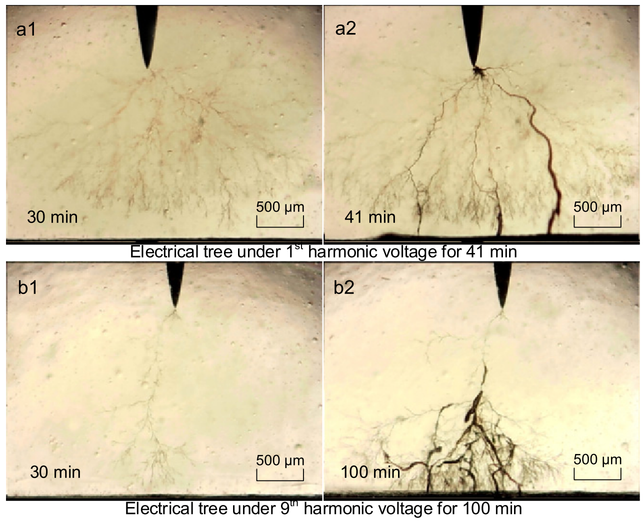

FIGURE 9. Two distinct reverse trees under harmonic voltage.

The breakdown is defined as the tree branch has traversed the insulation. However, the insulation is not destroyed immediately after the tree tip reaches the ground electrode in most of the samples tested under harmonic voltage or harmonic superimposed ±10 kV DC voltage. Comparing with harmonic voltage, it is apparent that the DC component has an obvious acceleration on electrical treeing process under superimposed voltage. With the increase of DC amplitude, the breakdown time decreases fast. The polarity effect can be seen from Fig. 8 that positive DC component leads to breakdown easier. With the increase of harmonic order, the breakdown time decreases at first and then increases under all kinds of superimposed voltages, which is in accord with the non-linear trend in tree length. Significantly, the breakdown time reaches a minimum value in 3rd harmonic superimposed DC voltage under all kinds of harmonic superimposed DC voltages. A similar result was obtained by literature [19], a minimum breakdown voltage at 170 Hz in cross-linked polyethylene.

In principle, the dielectric failure will happen immediately if the electrical tree reaches the ground electrode. However, exceptions happen under special voltage condition. The needle-plate system can remain relatively stable within minutes to days. In this case, the new tree channel generates from plate electrode toward needle tip during periodic voltage cycles and is named as reverse tree. The reverse tree experiment is reproducible, and similar results can be found in [20]–[22]. Typical reverse tree growth process is shown in Fig. 9. In Fig. 9a1, the filamentous branches are in light color and spread out over a large area. In Fig. 9a2, a thick and dark reverse tree channel partially bridges the needle-plate gap, and another two reverse tree channels grow toward the needle electrode by widening and darkening the previous tree channel. The tree bifurcations extended from the main channel also become dark, which indicates intense discharge within the tree channel. Finally, the revere tree forms a channel throughout the whole insulation, and the applied voltage falls to zero. Another typical reverse tree is shown in Fig. 9b1 and 9b2. Many reverse trees grow from the previous filamentous tree channel and partially bridge the insulation, but it ceases to propagate further to the needle electrode. The reverse tree channel fails to form a penetrated channel. In this case, it may take a considerable time to form the penetrated channel and cause insulation failure. However, the reverse tree causes great damage to the insulation and is well worth regarding. The formation of reverse tree is a complicated process that involves intrinsic material characteristic, electric field distribution, external testing environment and many other factors. The electrical tree growth and reverse tree formation will be discussed from the point of dynamic electric field distribution in Section 4.2.

IV. DISCUSSION

A. EFFECT OF CHARGE TRANSPORT ON TREE INITIATION AND ELECTRICAL DEGRADATION

Complicated physical processes happen in polymer aging such as mechanical fracture in presence of accumulated charge, bond breaking by avalanche thermal effect, and bond breaking by energy released during charge trapping or charge recombination [23]. The electrical treeing process is closely related to charge transport process that includes charge injection, charge trapping-detrapping and charge recombination. Under voltage excitation, the needle-plate system is a typical distorted field and the electric field at needle tip is extremely high. The high electric field can be calculated according to the Mason's formula [24]:

$$E_{\text{inj}} = E_{\max} = \frac{2U}{r\ln(1+\frac{4w}{r})} \quad (1)$$

where E_{inj} is the electric field at the needle tip, U is maximum value of superimposed voltage, r is curvature radius of needle tip and w is the distance between needle tip and plate electrode.

The local electric field is high enough to exceed the material dependent critical field and bring the charge carriers into high-mobility states [25]. The charge carriers transfer across the needle-dielectric interface due to the Schottky emission or field emission. For instance, electrons are injected into the polymer, and then fall into localized trapping center to form space charge under negative voltage [13]. Space charges can also be produced by partial discharge or field ionization [26]. The homo-injected charges accumulate around the needle tip, which leads to a shielding effect of electric field in the vicinity of needle tip as well as a field enhancement in the bulk of polymer. Finally, the charge injection will cease if the local electric field equals to the critical field. The final electric field can be calculated roughly as equation (2):

$$E_L = E_{inj} - E_{sc} \tag{2}$$

where the E_L is the local electric field, and the E_{sc} is the alleviated strength of injected charge.

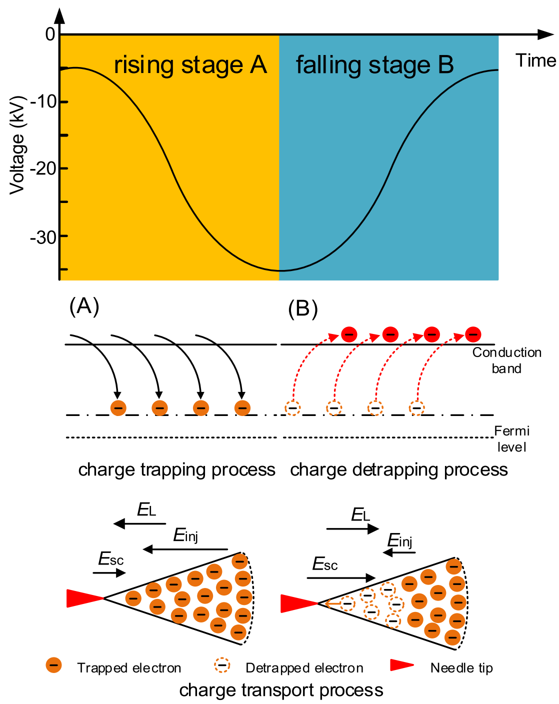

FIGURE 10. Charge transport process under harmonic superimposed −20 kV DC voltage.

Fig. 10 shows the charge trapping and detrapping processes after harmonic voltage is superimposed on −20 kV DC voltage. When the DC component is stressed on sample at first, the charges can jump over the potential barrier at metal-polymer interface and be trapped near the needle tip. After the harmonic superimposed DC voltage is generated, more electrons will fall into trap centers during the voltage rising stage A. In voltage falling stage B, electrons will detrap and move towards needle electrode when the superimposed voltage falls down. Some electrons detrap and move back due to its close proximity to needle tip, while other electrons away from needle tip remain trapped due to insufficient local field. This migration of charge carries will be repeated by the changing electric field during the periodic rising and falling stage of voltage. In this process, the polymer molecules will be broken into free radicals by the energy released during the trapping process of high-mobility electrons, more traps will be produced by the polymer chain scission due to collision with hot electrons. The produced free radicals and chain scissions will contribute to the formation of deteriorated region, which accelerates tree inception. Besides, ionization and charge recombination may occur in this deteriorated region and eventually initiate the electrical tree.

The property of charge carrier accounts for polarity effect in tree initiation under superimposed voltage. With the features of small mass and high mobility, it is easier for electrons to inject into the sample than holes [27], [28]. The large number of injected electrons will shield the high electric field at needle tip.

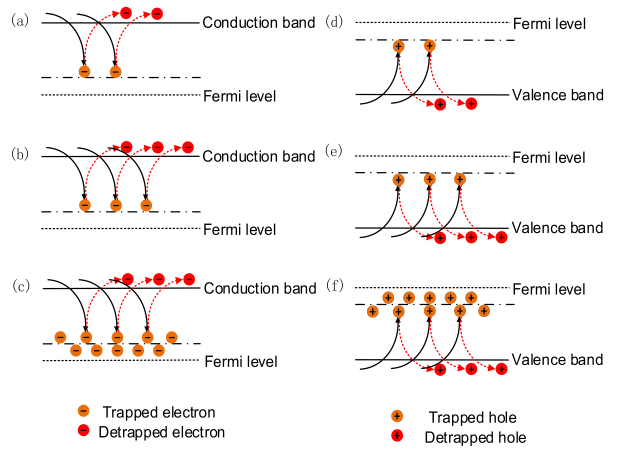

FIGURE 11. Charge transport process under different harmonic orders superimposed 20 kV DC voltage.

Fig. 11 interprets the effect of harmonic orders on charge transport process under superimposed voltage. When the 1st harmonic component is superimposed on the negative DC voltage, the electrons repeat the process that falls into and detraps from the trap center during the periodic voltage cycles (shown in Fig. 11a). The ceaseless trapping and detrapping processes cause the damage to insulation material, and finally the electrical tree is triggered at deteriorated region. With the increase of harmonic order, the injected electrons trapping and detrapping processes become more frequent (shown in Fig. 11b). The frequent charge transport process accelerates the formation of free radicals and shortens the time to form deteriorated region. Therefore, it is easier for electrical tree to initiate and the tree initiation probability increases. It is observed that charge accumulation is more severe with the increase of applied frequency [29]. With the further increase of harmonic order, large number of electrons are injected and trapped around the needle tip, but some electrons away from the needle tip remain trapped during the charge extraction process (shown in Fig. 11c). Those charges continuously accumulate around the needle tip and shield the electric field, which explains why the initiation probability decreases when harmonic frequency exceeds 150 Hz.

The hole transport process is shown on Fig. 11d-f. With the increase of harmonic order, the hole transport experiences a similar transfer process, it interprets the variations in tree initiation under harmonic superimposed positive DC voltages. However, the electric field fluctuation is more severe near the needle tip with injected holes because of the lower mobility and higher mass. As a result, it is easier to initiate electrical tree with positive DC component, which is shown in Fig. 7.

B. EFFECT OF ELECTRICAL FIELD ON TREE BREAKDOWN AND REVERSE TREE FORMATION

To interpret the tree growth and breakdown characteristics under harmonic superimposed DC voltage, the field-driven tree growth (FDTG) model provides some insightful explanations by considering the macroscopic spatial and temporal development of electrical tree growth [30], [31]. In this model, it is assumed that material damage in polymer insulation will occur if the local electric field E_L exceeds the critical electric field under divergent field, and the mass of damage depends on the magnitude of E_L above the critical field. If the electrical tree is conducting during the partial discharges within the tree channel, the E_L will be modified by effectively shortening the needle-plate gap as well as increasing the apparent curvature radius of needle tip. The tree length can be effectively equal to a conducting hyperboloid of hyperbolic radius. Therefore, the E_L can be calculated according to the equivalent needle-plate system. The FDTG model gives the maximum field E_{max} along the needle axis as [31]:

$$E_L = E_{\max} = \frac{2Ua}{(L+r)\ln[(a+1)/(a-1)]} \quad (3)$$

$$a = \left(1 + \frac{L+r}{w-L}\right)^{1/2} \quad (4)$$

where L is the tree length, and the a is the shape parameter. Before the tree is initiated, this equation is consistent with the Mason's equation (1). Fig. 12 shows the non-linear characteristic between the E_L and tree length L under harmonic voltage, calculated by equation (3). A typical U-shape curve is found, and it can be divided into three regions. In sharp dropping region A, the local field has an extremely high value near the needle tip due to the needle-plate geometry. The high-intensity electric field changes with periodic voltage cycles. The electrical tree initiates and propagates due to the repetitive charge transport process. As the electrical tree continuously propagates further to the insulation region, equivalent radius of needle tip increases and the E_L keeps falling down. In smoothly varying region B, the E_L changes at a relative slow speed, and it reaches a minimum value when the electrical tree extends to half of the gap between the needle tip and plate electrode. Then it comes to the sharp rising region C, the E_L increases as the tree extends toward the plate electrode. The FDTG model fits the experiment results and it is found that stagnate stage always occurs when electrical tree ceases to extend at certain tree length [32].

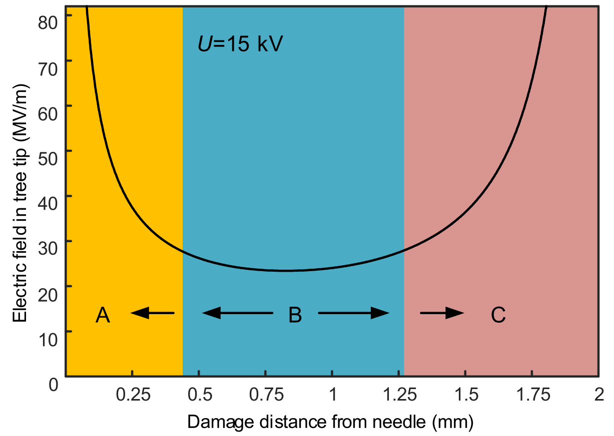

FIGURE 12. Local electric field at the damage perimeter as a function of damage extent under 15 kV harmonic voltage.

During the experiments without DC voltage, the needle-plate system can remain stable even when the filamentous branch has bridged the epoxy resin insulation. It seems that the filamentous branch does not lead to instant failure after reaching ground electrode. The filamentous branches are assumed to be non-conducting or less conductive than the dark branch due to the features of slender structure and light gray color [17]. A complete conductive path cannot form immediately within the whole insulation, and hence the needle-plate system remains stable. However, the local electric field is much higher at the tree tip due to its proximity to plate electrode, which is enough for discharges occurring, forming the reverse tree channels. It is obvious that reverse tree channel is darker and wider than the previous filamentous branch channel. The dark tree channel indicates that the discharge intensity and oxidization effect are more severe within channel. The chemical decompositions product deposits in reverse tree channel, so it can be supposed to be conducting or semi-conducting. The conductivity of reverse tree channel shortens the effective needle-plate distance. The reverse tree keeps growing toward needle tip due to the relative high electric field. This also accounts for the phenomenon that tree tip near the plate electrode bifurcates and darkens. The electrical tree near the needle tip gets dark, but it stops growing down due to the electric field modified by the conductive channels. The reverse tree tends to grow along the previous tree channel for the existing tree channel is more vulnerable than the insulation. The reverse tree will cease to extend if the electric field is below the threshold field (shown in Fig. 9b).

When harmonic voltage is superimposed on DC voltage, it is obvious that the DC component will strengthen the local electric field according to the equation (3). The variable high electric field leads to severe discharges during the charge transport process, which accelerates the tree growth. Therefore, the darker branch or dense bush can be found near the needle tip in Fig. 1 and Fig. 4. When the filamentous branches extend to the plate electrode, the electric field produced by this combined voltage is high enough to lead to instant failure.

Consequently, with the increase of DC amplitude, the failure tends to occur in a shorter time after tree tip reaches the ground electrode.

V. CONCLUSIONS

Electrical treeing process and reverse tree growth in epoxy resin under different harmonic superimposed DC voltage are investigated in this paper. The electrical tree growth depends on DC amplitude and harmonic order under superimposed voltage. The reverse tree has been found in experiment, and is explained by FDTG model. The following conclusions can be drawn in the paper.

1) Under different harmonic orders, the electrical tree length increases with the increase of DC amplitude. With the increase of harmonic order, the tree length shows a non-linear trend that increases at first and then decreases. The low-order harmonics lead to more damage areas under superimposed voltage. More attentions should be paid to low-order harmonics during the daily operation of power equipment.

2) With the existence of DC component, the filamentous branches decrease in number and get longer in length under harmonic superimposed DC voltage. The increasing DC amplitude can cause an acceleration on tree initiation, growth and breakdown process under superimposed voltage. The positive DC component causes a shorter breakdown time than the negative DC component. The charge transport process has been discussed under different harmonic superimposed DC voltages.

3) In this experiment, the reproducible reverse tree growth is found in needle-plate system under several superimposed waveforms. The new tree channel generates from plate electrode and is named as reverse tree. The FDTG model has been employed to interpret it from the perspective of electric field distribution.

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BOXUE DU (SM'04) is currently a Professor and the Director-Founder of the Institute of High Voltage, School of Electrical and Information Engineering, Tianjin University, China. He has published three books and four book chapters in polymer dielectrics, and authored about 400 papers and more than 110 of them published in IEEE Transactions. His research interests include dielectric failure mechanisms of polymer insulating materials, electrical insulation technology, and the application of polymer dielectrics under various extreme environments such as cryogenic, high temperature, gamma–ray irradiation, and high-intensity magnetic field.

MENG TIAN was born in Hubei, China, in 1995. He received the B.Eng. degree from Tianjin University, where he is currently pursuing the M.Sc. degree in high voltage engineering and automation. He is currently engaged in research on electrical tree aging problem of epoxy resin. His current research interests include the breakdown phenomena of polymer insulating materials and space charges analysis in polymers.

JINGANG SU was born in Hebei, China, in 1988. He is currently pursuing the Ph.D. degree in high voltage and insulation technology with the School of Electrical and Information Engineering, Tianjin University. He is currently engaged in research on aging problem of EPDM. His current research interests include partial discharge phenomena and the detection methods of polymer insulating materials in power cables.

TAO HAN (M'16) was born in Shandong, China, in 1987. He received the Ph.D. degree in high voltage and insulation technology from the School of Electrical and Information Engineering, Tianjin University. He is currently engaged in research on aging problem of silicone rubber. His current research interests include the diagnostic testing of electrical insulation and failure analysis of high voltage power cable.