Electrical Tree Structures in Negative DC Fields Superimposed with AC Ripples

Electrical Tree Structures in Negative DC Fields Superimposed with AC Ripples

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Abstract- **This paper explores in detail tree structures grown in negative DC fields superimposed with AC ripples (previously named 'slim bouquet' structures). Fine channels which grow during negative DC ramp down are included in the study, and trees grown in purely 50 Hz AC fields are considered for comparison. A state-of-the-art 4K optical microscope was employed to observe tree structures with both transmitted and reflected light. With reflected lighting, dark stem channels and light yellow quasi-2D leaf-type structures were identified in AC trees. Raman spectroscopy suggested the presence of carbon decomposition products within dark stem channels. Bouquet structures were found to have similarities to leaf-type structures as both appeared as light yellow pixels under reflected lighting. Pictures comprising images taken at different focal planes are shown to be powerful tools in understanding tree morphology.**

I. Introduction

Electrical treeing in polymeric insulation materials refers to the appearance and development of tree-like channels resulting from localized electric field enhancement. Insulation, for example XLPE (cross-linked polyethylene) in extruded power cables, fails when these tree channels bridge the insulation thickness [1].

HVDC (high-voltage direct current) is a highly efficient way to transmit electricity, and its application has seen a rapid growth with the increased share of electricity generation by renewables [2][3]. An HVDC transmission network typically consists of a) DC links which can be subsea or underground cables and overhead lines, b) two power converters, one converting AC to DC and the other vice versa, and c) filters and reactors to obtain good power quality. AC-DC converters and coupling to other systems are sources of AC ripples and harmonics traveling along DC links [4].

While electrical treeing in a needle-plane geometry has been extensively studied in AC fields, few papers have reported treeing in working conditions in HVDC networks: neither in pure DC fields nor under DC stresses superimposed with AC ripples. Our previous papers are the first where the DC component has been set so high (+45 kV [5], -60 kV [6]) while the AC component is relatively low (5 kV pk [5], 7 kV pk [6]). Particularly, a new type of tree has been identified in low-density polyethylene (LDPE, base material of commercial XLPE cables) under high negative DC voltage superimposed with AC ripples at '-60 kV DC ± 7 kV pk AC' (denoted 'N60 ± 7') and named the 'slim bouquet' structure [6]. The treeing area features in 2D transmitted light images as a silhouette filled with dark pixels within a short length (<200 µm, one tenth of the tip-plane distance) and a narrow width (<110 µm) even after long periods of voltage application. The narrow treeing area filled with dark pixels gives the slim bouquet silhouette. Moreover, fine channels (the name for tree channels with diameter of ~1 µm [7]) were seen to develop from the existing bouquet structure during DC ramp down, no matter whether or not the AC component was applied across the test sample when DC began to decrease [8].

This work further explores bouquet and fine channel structures in LDPE grown at 'N60 ± 7' [6][8], and compares these with trees grown in LDPE in pure AC fields. A cutting-edge optical microscope is employed to reveal details of tree structures. Chemical information within the tree channels is provided by Raman spectroscopy.

II. Experimental Description

A. Experimental Setup

Electrical trees were grown in LDPE in a needle-plane geometry (tip radius r = 3 µm, tip-plane distance d = 2.23 ± 0.23 mm). To obtain a high negative DC voltage superimposed with AC ripples, a DC voltage source and an HV amplifier as an AC voltage source are connected in parallel. Detailed experimental arrangements are available in [6]. The test setup of treeing under purely AC fields is shown in Fig. 1, adapted from the 'DC ± AC' circuit [6]. Therefore, there is a DC isolating capacitor in the figure. The test voltage was 12 kV pk and PD background noise level was ~1.5 pC.

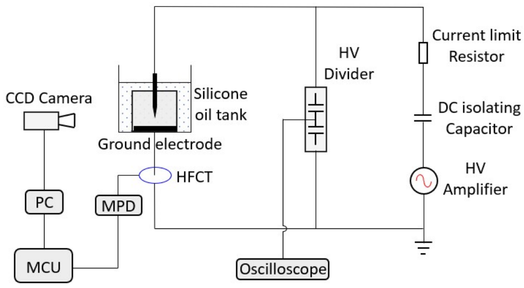


Fig. 1. Test setup of treeing in purely AC fields

B. Optical Images

After voltage application, samples were observed under a 4K ultra-high accuracy microscope (Keyence VHX-7000) to further explore tree structures. The microscope provides two lighting modes: transmitted and reflected. In optical microscopes higher magnification results in a smaller observation area and therefore less light intensity, so some samples were polished thinner and smoother with diamond paste (up to 0.25 µm grade) to get better light transmission and reflection before observation under the microscope.

C. Raman Spectroscopy

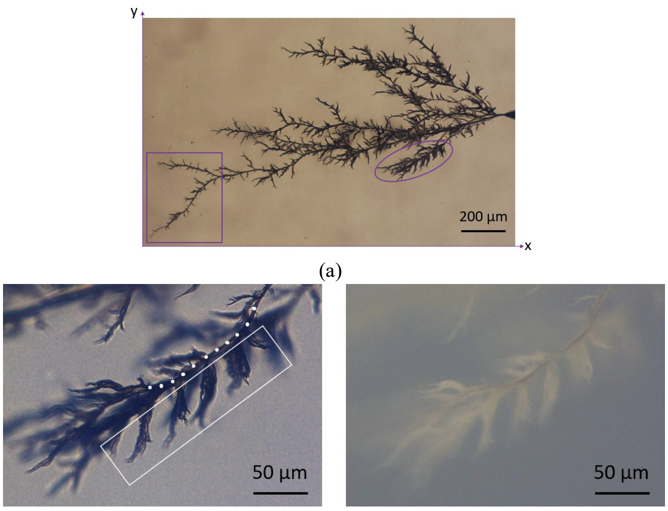
Raman spectroscopy is a chemical analysis technique based on Raman scattering between chemical bonds in a material and the laser source in a Raman spectrometer. A HORIBA LabRAM HR Evolution spectrometer was employed. The wavelength of laser beam was 633 nm. Beam calibration was done by a silicon wafer with a peak at 520 cm^{-1}. The beam spot was around 5 µm in diameter through a x100 objective lens packaged with the spectrometer.

III. Results

A. Optical Images of AC Trees at 12 kV pk AC

To facilitate the comparison, optical images of a tree grown at 12 kV pk AC for ~52 minutes (sample S1) are first displayed in this section, followed by those of a tree grown at 'N60 ± 7' (sample NS6 in [6]) in Section III-B.

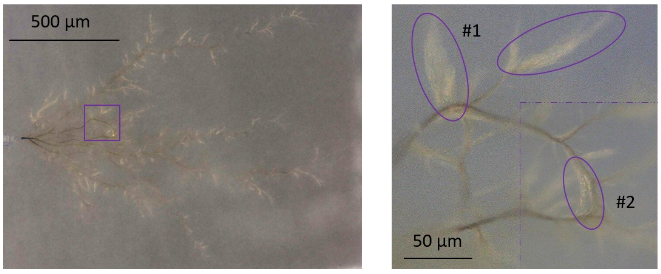
Fig. 2a shows the whole tree structure of S1 as black pixels, which is not surprising, as the sample was illuminated with transmitted lighting when taking the image. It is a depth composition generated by stacking images captured on different focal planes. In this way tree channels which are focused on different planes can be displayed together. Fig. 2b shows the encircled channels in 2a with transmitted lighting. The structure included in the white rectangle of 2b resembles leaves along a stem which is indicated by the white dots. When the lighting is switched to reflected mode without change in focal planes (i.e. without change in sample stage height), as shown Fig. 2c, the leaves appear as light yellow pixels while the dotted stem channel remain as black and brown pixels. Therefore, these two structures are named here leaf-type structures and dark stem channels.



(b) (c)

Fig. 2 Optical images of S1: (a) composition with transmitted lighting, the circled channels in (a) with (b) transmitted lighting and (c) reflected lighting.

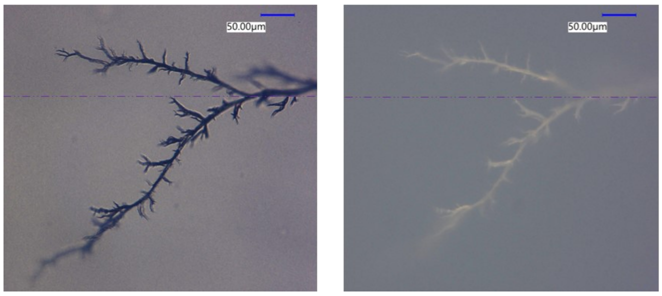
Fig. 3a displays a composite section image within S1 sliced along the x-axis in Fig. 2a, and the squared area in 3a is enlarged in Fig. 3b. The latter is a collage of images with dashed lines showing borders, as the two parts were on different focal planes. With leaves so close to the upper surface of the exposed section (yielding a clearer image), leaves encircled by ellipsoids at #1 appear as quasi-2D structures like botanical leaves. Channels at #2 seem to be merged. Such a feature has only been presented previously in a 3D volume rendering by Nano-XCT [9]. Furthermore, at the merging channel segment there is another ultra-thin 'leaf'.



(a) (b)

Fig. 3. A section within S1 sliced along x-axis in Fig. 2a: (a) the composite image with reflected lighting, (b) the squared area in (a) enlarged.

Fig. 4 displays channels at the distal end of the tree (from the area marked by a square in Fig. 2a). Though the main branches or stems can still be recognized, there are no dark color ones. All channels appear light yellow under reflected lighting, like the leaf-type structures. Note that these images are also a collage as the two channels could only be focused on different planes. The dashed line shows where the images meet.



(a) transmitted lighting (b) reflected lighting

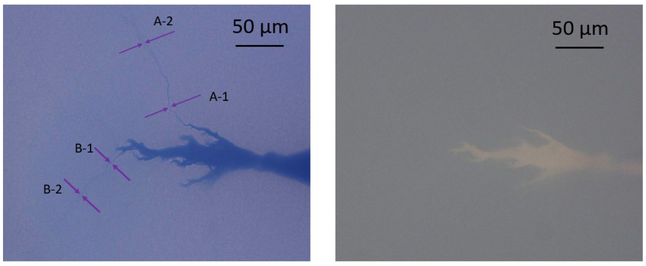
Fig. 4. Optical images of tree channels at the tree tip highlighted in Fig. 2a.

B. Optical Images of Bouquet Structures and Fine Channels

Images of a bouquet structure are displayed in Fig. 5a with transmitted light and 5b with reflected light. Bouquet structures also appear as light yellow pixels with reflected lighting, showing similarity to the leaf-type ones in Fig. 2 and the distal channels in Fig. 4 generated in AC fields.

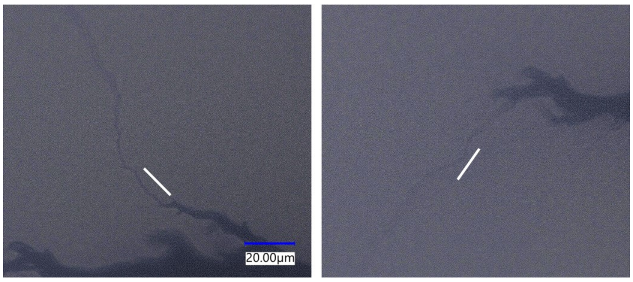
Purple arrows in Fig. 5a indicate fine channels formed during DC ramp down after the AC component first decreased to zero in this sample [8]. Segments A-2 and B-2 appear thicker and blurrier than A-1 and B-1 because the former is out of the focal plane while the latter is in focus.

Fig. 6 shows resolution enhanced images of fine channel segments A-1 and A-2 from Fig. 5, using the HDR (High Dynamic Range) technique integrated in the microscope software. The white lines in the figure have a width of 1 μm, which is comparable to the diameter of the focused fine channel segments next to them.



(a) transmitted lighting (b) reflected lighting

Fig. 5. Optical images of a bouquet structure at 'N60 ± 7' after 318 min growth and fine channels developed during DC ramp down.



(a) fine channel segment A-1 (b)fine channel segment B-1

Fig. 6. Optical images of focused fine channel segments in Fig. 5. The scale bar of 20 μm applies to both.

C. *Chemical Information*

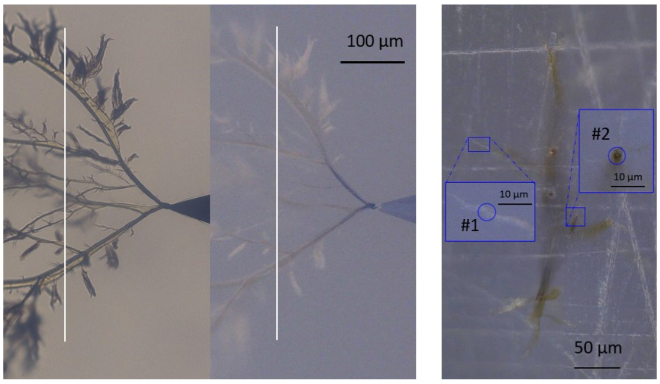
Much effort has been made to expose sections of a slim bouquet structure with the intention of taking SEM images followed by a Raman test. However, the structure is <200 μm in length and has no dark stem channels as a location reference when either polished or sliced with an ultramicrotome (Leica EM UC6). With the ultramicrotome, real-time section examination is extremely difficult because the magnification of its fitted microscope is insufficient. Therefore, another AC tree (sample S2 grown at 12 kV pk AC for ~52 minutes) was polished to do a Raman test.

Fig. 7a displays representative dark stem channels which are in front of the needle tip with vertical lines indicating the exposed section. Fig. 7b is the section image with two spots circled which were focused with the laser beam. Spot #1 is in a channel tip and #2 is in a channel section. They appear different with reflected lighting. The channel in Spot #1 is light yellow or even white (considered as comparable to a slim bouquet structure), and that in Spot #2 is brown and black.

Fig. 8 plots the Raman spectra of the channel tip (#1) and the dark stem (#2), together with a random spot on the surface of the LDPE base (#3) and one on a standard graphite bulk (CAS 7782-42-5, #4). The channel tip shows the same spectra as the LDPE base. Graphite shows the D peak at ~1330 cm^{-1} and the G peak at ~1589 cm^{-1}. The G peak was also detected from the dark stem channel section.

D. *PD Signals*

Fig. 9 displays the PD magnitude (on the weighted average every 300 ms by Omicron® PD measurement package) from sample S2 against growth time to facilitate discussion in Section IV. Tree growth was accompanied by PDs and events of greater than hundreds of pC existed during most of the period of tree growth.



(a) (b)

Fig. 7. Sample S2: (a) images in front of needle tip with vertical lines indicating section exposure, (b) section image and spot indication under Keyence microscope.

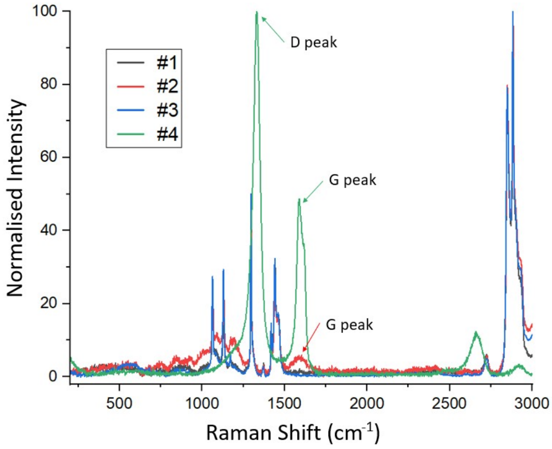


Fig. 8. Raman spectra of channel tip (#1), dark stem section (#2), LDPE base (#3) and standard graphite (#4).

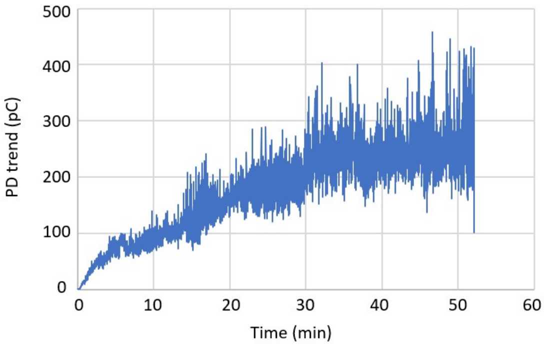


Fig. 9. PD trend variation of S2 against growth time

IV. Discussion

The high resolution optical microscopy gives an insight into tree structures grown at different voltages. The integrated depth composition displays tree channels on various focal planes in one image. The HDR technique revealed sub-micron details. The reflected lighting mode of the microscope, PD measurement and Raman spectroscopy helped explore the nature of different channels.

A. AC Trees at 12 kV pk AC

The tree in Fig. 2a can been described as a branch tree [10], which was initiated and grown in LDPE with the standard needle-plane geometry at 12 kV pk AC. Quasi-2D leaf-type structures in AC branch trees were clearly presented and named for the first time. They appeared as light yellow pixels with reflected lighting and usually grew along main branches including dark stems. An ultra-thin leaf was even spotted at the merging channel segment in Fig. 3b. Dark stem channels showed a G peak in the Raman spectra in Fig. 8. The G peak is one of the signature peaks of graphite and its existence suggested carbon decomposition products within channels [11][12]. It is attributed to the repeated PD erosion within channels, as shown in Fig. 9 with PDs of hundreds of pC. PD propagation within main branches was also supported by the light emission distribution of PDs in branch trees [10]. The channel tip which appeared as light yellow pixels under reflected lighting had almost the same Raman spectra as the LDPE base, showing no sign of carbon decomposition products. It, along with leaf-type structures, is thought to be mechanical cracking rather than driven by PD erosion.

B. Bouquet Structures and Fine Channels

The slim bouquet structure forming at a high negative DC superimposed with AC ripples appeared as light yellow pixels under reflected lighting (Fig. 5). Like other structures which were also seen as light yellow pixels with reflected lighting, the bouquet was thought to lack carbon decomposition products in most of the structure. This view is supported by, compared to purely AC cases, the much less active PD occurrences in the bouquet structure, where the maximum PD magnitude in PD clusters was less than 15-20 pC [6].

Fine channels have been reported in detail in epoxy in AC fields [13], but rarely identified clearly in LDPE. In the negative DC superimposed with AC ripples ('N60 ± 7'), they were found to develop during DC ramp down from the existing bouquet structure [8]. The diameter was measured in this work to be ~1 µm, which is a typical definition for fine channels [14].

V. Conclusions

This work explored tree structures of different types in LDPE, taking advantage of a 4K microscope and Raman Spectroscopy. The conclusions are as follows:

- The appearance of tree structures with reflected lighting best suggests their nature.
- In branch trees grown at 12 kV pk AC, dark stem channels appeared as brown and dark pixels with reflected lighting. The G peak could be detected in Raman spectra in the channel section and reinforces the view that this is evidence of carbon decomposition. This is thought to result from PD erosion within the channels. Quasi-2D leaf-type structures which appeared as light yellow pixels under reflected lighting were identified. They usually grew from and along stem channels. Channel tips were also seen as light yellow pixels.
- The slim bouquet structure appeared as light yellow pixels with reflected lighting. With much less active PD activity, bouquet was thought to be mechanical cracking, and not subject to carbon decomposition.
- Fine channels formed during DC ramp down from existing slim bouquet structures were clearly identified to be ~1 µm diameter for the first time with clear optical images.

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