Electrical treeing in insulating resins with silica nanofillers

Josef Niedernhuber, Josef Kindersberger
Lehrstuhl für Hochspannungs- und Anlagentechnik
Technische Universität München
Munich, 80333 Germany
josef.niedernhuber@tum.de

***Abstract*— The study addresses the treeing-performance of unsaturated polyester resins with and without silica nanofillers and epoxy resin. Specimens with embedded needles mounted on a grounded plate are used. Time to electrical tree initiation, time to breakdown and growth behavior are determined. The influence of filler loading on the treeing performance as well as the effect of voltage amplitude are investigated. The results show that the resistance to treeing strongly depends on the type of matrix material used. While 1 wt. % nanofiller leads to improved resistance to electrical treeing, 5 wt. % worsens the treeing performance.**

Keywords—treeing; nano filler

I. Introduction

Electrical treeing is an important degradation mechanism in polymeric electrical insulation systems. In particular, the lifetime of electrical machines, switchgears and bushings may be affected by treeing [1, 2]. To extend the durability of the equipment, tree inception has to be delayed and propagation of treeing should be slowed down [3]. It is known that the properties of insulating materials can be changed by adding just a few percent of nano filler. For the treeing resistance, researchers found out that the addition of nano filling material results in an increase of time to breakdown and a prolongation of the incubation period [4].

II. Experimental

A. Materials

Two unsaturated polyester resins (UP-resin A and B) and one epoxy-resin were examined as to their resistance to electrical treeing. The epoxy-resin is a bisphenol-F type single-component impregnating resin. UP-resin A and resin B are two different kinds of single-component resins free of monomers. UP-resin A was filled with different loadings of a hydrophilic nano-silica (1 wt. %, 5 wt. %) with a primary particle size of 12 nm. Mixing was realized mechanically by means of a disperser. Due to hydrogen bonding between filler and the base-polymer, viscosity of the uncured resin raises with the filler loading. After curing the dispersion of filler was checked using a FIB (focused ion beam) [5]. Nanoparticles are evenly distributed within the insulation material and no agglomerates are visible for both filling degrees, i.e. 1 wt. % and 5 wt. %.

B. Specimens

To characterize the investigated materials a tip-plane arrangement was used. This configuration is a common way to determine the resistance to electrical treeing [6]. The length, width and height of the sample were 15 mm, 6 mm and 10 mm, respectively. Needles with a tip-radius $r = 5$ µm were placed in the casting mold before curing. The distance d between the tip of the needle and the bottom of casting mold and ground electrode respectively was set to 3,5 mm (Fig. 1).

The curing was carried out at 120°C (UP-resin A and B) and 150°C (epoxy-resin), respectively. Low curing temperatures were used to reduce mechanical stress that can cause cracks or gaps especially around the tip of the needle. To achieve completely hardened specimens, time for curing had to be extended (Arrhenius equation). To avoid any influence of humidity on the results, specimens were stored at defined ambient conditions (50% RH, room temperature).

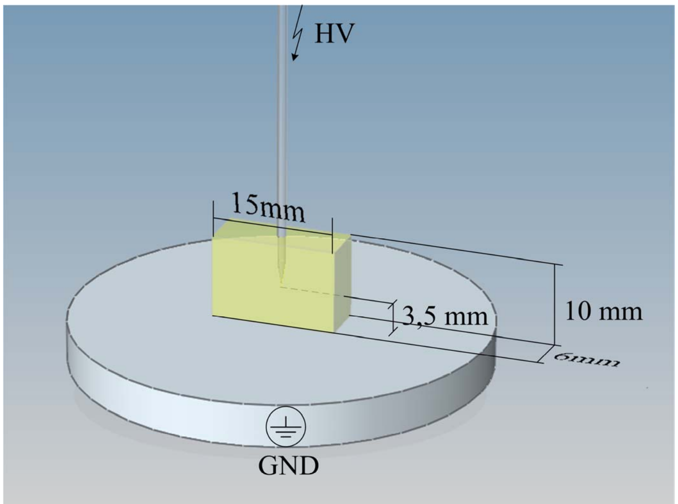

Fig. 1. Electrode arrangement and specimen dimensions for the electrical treeing test.

C. Test-conditions

The experiments were carried out at power-frequency ($f = 50$ Hz). Applied voltage U was varied in the range between 7 kV and 25 kV rms. The test cell was immersed in insulating ester to avoid flashover. The bottom side of the sample is coated with conductive varnish to establish good electrical contact between the specimen and the ground-electrode. Tree inception is detected visually by means of a camera focusing the tip of the needle whereby the detectable minimum tree length is approximately 15 µm. The shortest trees detected right after inception were 40 µm in length.

III. Results and Discussion

A. Tree inception

Voltages from 7 kV to 25 kV rms were applied for specimens of neat UP-resin A with a sample size of $n = 3$ (for 7 kV: $n = 1$). The results show that the tree initiation time t_i decreases with increasing applied voltage U (see Fig. 2).

The tree initiation process is associated with charge injection from the needle electrode – in real insulations from metallic inclusions [7, 8]. One possible route to the formation of trees is that injected charge leads to impact excitation of molecular species and thus chemical degradation [7]. Another possible theory proposes a breaking of bonds by radiation emitted during charge recombination [7]. The typical correlation of time to inception t_i and voltage U is $t_i \propto U^{-n}$ [8-9]. These findings are confirmed in our study. The correlation between inception time t_i and the voltage U follows $t_i \propto U^{-n}$ with $t_i = 35{\cdot}10^6\ U^{-5}$ (see Fig. 2, dashed line).

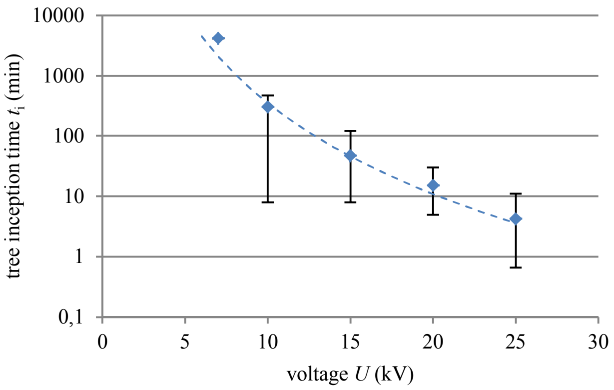

Fig. 2. Median value of tree inception times depending on test voltage for unfilled UP-resin ($n = 3$, for 7 kV: $n = 1$). Bars represent maximum and minimum value. Dashed line: $t_i = 35{\cdot}10^6 \cdot U^{-5}$.

Different materials are investigated with respect to their tree-inception times at 20 kV (Fig. 3). For the unfilled resins, UP-resin A shows the highest median of the inception time $t_i = 10$ min, while the values for the epoxy-resin ($t_i = 1$ min) and UP-resin B ($t_i = 0{,}5$ min) are significantly lower. In particular for UP-resin A, adding 1 wt. % nano-silica ($t_i = 60$ min) increases the inception-time, whereas 5 wt. % ($t_i = 2$ min) filler leads to lower values of t_i compared to neat UP-resin A.

Assuming that differences between the neat polymers are material-dependent, variation of t_i for filled and unfilled UP-resin A needs further explanation. It is confirmed that tree inception is caused by transfer of energy from the electrode to the material [7]. This energy causes a breaking of bonds in the polymer and thus degradation. Longer times to tree inception might be an indication of higher bonding forces in the polymer – which can be attributed to adding 1 wt. % nanofillers. Hints for higher bonding strengths in nanocomposites are a phenomenon which is often reported [10, 11].

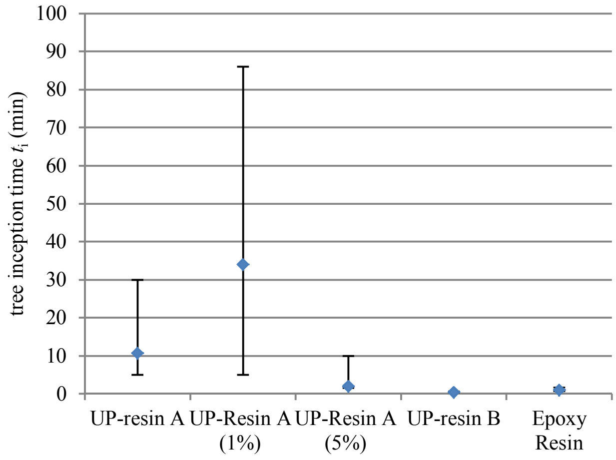

Fig. 3. Median of tree inception times t_i for different materials. Bars represent maximum and minimum value of t_i ($V = 20$ kV, $f = 50$ Hz).

The findings of a maximum value of enhanced properties at a certain filling degree can be explained by the interphase-volume-model that assumes a layer of interface surrounding the filler particles [12]. In this case, the performance for 5 wt. % filled nanocomposites is even worse than for neat UP-resin A. This finding cannot be explained by the model and needs further investigation.

B. Tree propagation

Subsequently, the propagation properties of filled and unfilled UP-resin A as well as neat epoxy-resin were investigated. Fig. 4 shows the median of the extension of the trees of unfilled UP-resin A towards the ground electrode at different levels of voltage within the first 100 h of tree growth, i.e. the origin of the x-axis equals t_i. The evaluation is based on pictures taken by the camera-system. Sample size is $n = 3$ for each level of voltage.

At all voltages a rapid growth of the trees right after inception was detected, whereon for most specimens the tree growth decelerates until it stops eventually. There are two basic shapes of treeing-structures. Depending on the polymer, the radius and material of the needle electrode and the test voltage, branch-like or bush-like shapes of the trees are reported [13]. Combinations of the basic shapes to form a bush-branch structure are possible, in addition. All specimens in this study that show a deceleration to no further growth of the trees have a bush-like shape (see Fig. 5-1). The expansion of the trees shows a minimum at $U = 15$ kV.

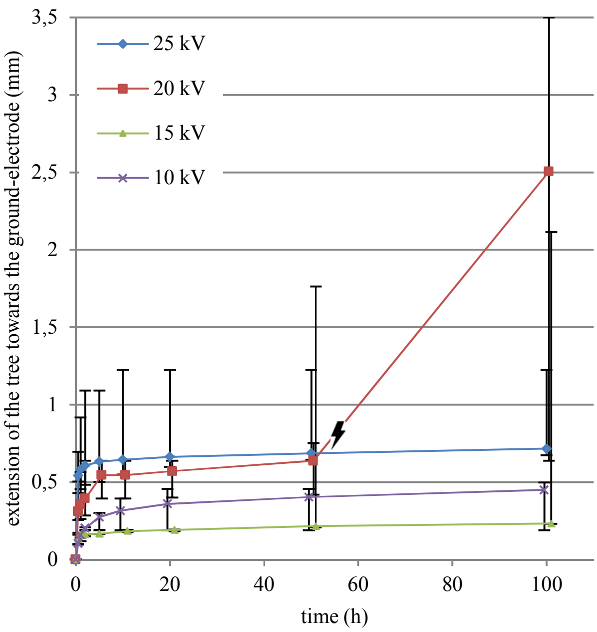

Fig. 4. Expansion of the longest tree channel directed towards the ground electrode depending on time. 0 h equals the inception time. The lightning mark indicates the time of breakdown of one specimen. Experiments are carried out at different voltage levels with unfilled UP-resin A (f = 50 Hz, r = 5 µm, d = 3,5 mm).

Two specimens stressed with U = 20 kV showed a different behavior: For specimen 2 (see Fig. 5-2), a branch-like structure developed from the bush-like structure after 70 h of testing. This bush-like tree grew to an extent of 2,5 mm within another 30 h. After that, no further growth can be observed for 100 h of voltage stress. Specimen 3 (see Fig. 5-3) showed a stable bush-like tree from hour 5 of testing onwards. After 50 h of stress, a fast growing branch developed reaching the ground electrode within another 5 h of testing.

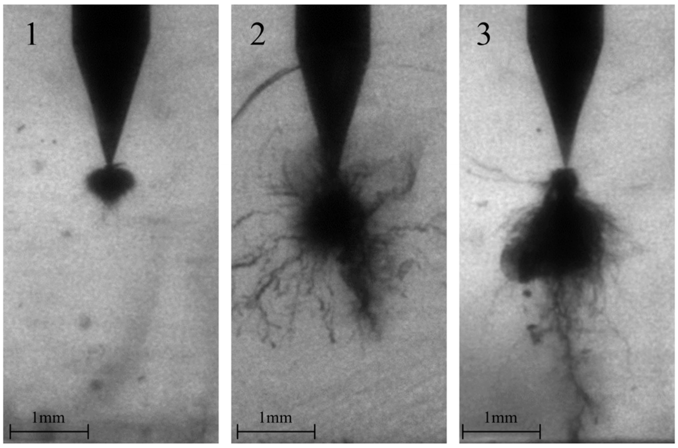

Fig. 5. UP-resin A treeing-needles (r = 5 µm) stressed with 20 kV, 50 Hz.
1: After 100 h, bush-like. 2: After 100 h, bush-branch structure.
3: After 60 h, bush-branch with spike, breakdown.

High testing voltages abet the occurrence of bush-like tree structures, whereas lower voltages yield to branched trees [6].

The bush-branch-transition for UP-resin A at low testing voltages was not observed in this investigation.

The occurrence of different shapes of trees using identical test conditions and materials needs further investigation. Variations of internal mechanical stress due to dissimilar shrinking in the casting molds could be a possible reason for the big scatter and changes of the tree shape. Internal mechanical stress is supposed to be a factor which influences the treeing properties [14].

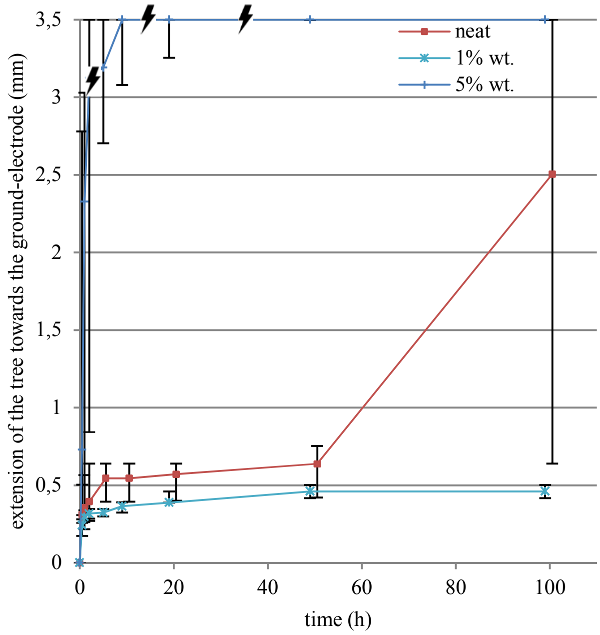

Fig. 6. Median of the expansion of the longest tree channel directed towards the ground electrode depending on time (n = 3). 0 h equals the inception time. The lightning mark indicates the time of breakdown of one specimen. Experiments are carried out at 20 kV with unfilled and filled UP-resin A (f = 50 Hz, r = 5 µm, d = 3,5 mm).

Fig. 6 shows the median of tree expansion of UP-resin A with different loadings of silica-nano-filler tested at 20 kV (n = 3). Specimens filled with 1 wt. % show bush-like tree structures with slightly smaller extent than for the neat material (see Fig. 7-1, 7-2). Branch-like tree structures leading to breakdown are observed using 5 wt. % silica filler (see Fig.7-3). The median of the time to breakdown for UP-resin A with 5 wt. % is t_b = 14,5 hours.

For the tree propagation of UP-resin A, the tendency of an improvement of treeing performance for 1 wt. % filler content as well as a worsening of the resistance to tree propagation for 5 wt. % filler-content compared to neat resin is observed.

Epoxy-resin shows bush-like trees with continuous growth. Experiments were carried out with U = 20 kV. The time to breakdown t_b is in the range between t_b = 0,75 h and 3,32 h with a median of t_b = 1,1 h.

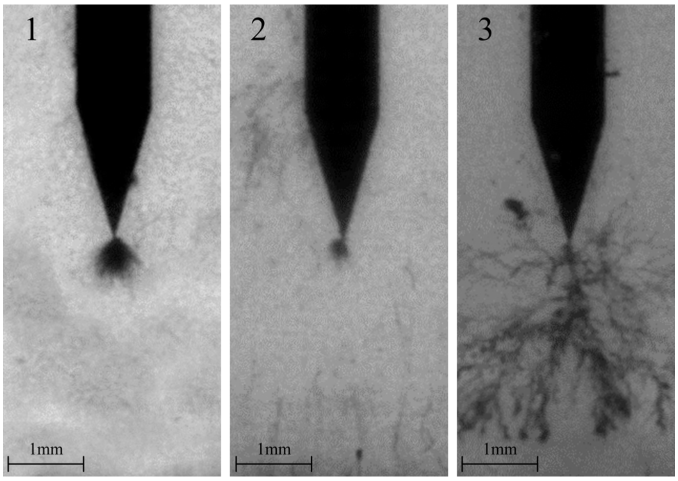

Fig. 7. Different forms of treeing for UP-resin A. The photos show the needle tips for different filler contents after 5 h of testing at 20 kV.
1: neat UP-resin A, 2: 1 wt. % filler content, 3: 5 wt. % filler content.

This behavior is unexpected since silica nano fillers are supposed to improve the resistance to electrical treeing significantly [15, 16]. For the time being no explanation can be found for the significant worsening of the treeing resistance at 5 wt. % filler content. This subject will be studied further on.

IV. Conclusion

Results for the electrical treeing properties of UP-resins, UP-resin nanocomposites and epoxy-resin containing tree initiation characteristics as well as tree propagation properties are presented. The following can be concluded:

- Tree inception time t_i and the shape of the trees depend on the kind of matrix material used. Neat UP-resin A shows higher values of t_i than UP-resin B and epoxy-resin.
- Tree inception time t_i in UP-resin A is dependent of the applied voltage U and follows $t_i = 35 \cdot 10^6 \cdot U^{-5}$.
- The use of 1 wt. % silica nano filler prolongs the incubation period and reduces the speed of tree propagation. 5 wt. % silica nano filler content has the opposite effect.
- Neat UP-resin A as well as 1 wt. % nanocomposite show slowly growing bush-like tree structures. 5 wt. % nanocomposite results in fast-growing branch-like shapes of the tree.
- At the same experimental conditions, different shapes of trees for neat UP-resin A may occur.

V. Acknowledgment

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