New insulating materials for next generation of HVDC cables - methods for evaluation of degradation phenomena by electrical treeing

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ABSTRACT

The ongoing in Sweden research activities aim to elaborate new material concepts that can be applicable in designing and manufacturing high voltage direct current (HVDC) cables for very high voltage levels, up to 800 kV. This task focuses on investigating possibilities provided by use of materials containing nanofillers and voltage stabilizers. Variations in breakdown strength, electrical conductivity and control of space charges with temperature and composition as well as their stability during long-term operation are investigated. This paper describes a part of the work that concentrates on elaborating a robust methodology for testing material resistance to electrical tree inception. It is argued that AC treeing test under ramped voltage may effectively be used for screening candidate materials for applications in HVDC cable insulation.

KEYWORDS

HVDC cable; Polyethylene insulation; Degradation; Electrical teeing; Testing method;

INTRODUCTION

Important factors that determine the performance of insulating materials in high voltage direct current (HVDC) cables are the variation in electrical conductivity with temperature and composition, the control of space charge, electrical stress distribution, breakdown strength, and the stability of these factors with time under operating conditions. In this respect, numerous attempts have been undertaken worldwide to improve the quality of polyolefin compounds for HVDC applications. In Sweden, a number of research groups work jointly today on investigating the possibilities arising from the use of materials containing nanofillers and voltage stabilizers, which has been made possible thanks to the financing provided by the foundation for Strategic Research (www.stratresearch.se). Six different strategies are evaluated for reaching project goal for meeting in three focus areas, as headlined in Fig. 1.

The initial project tasks are accomplished by an efficient high-through-put research effort involving testing the different strategies, using small probe volumes. These initial studies concentrate at the present stage on (i) manufacturing of high quality nanofillers and modifying their surface, (ii) synthesizing suitable voltage stabilizing additives, (iii) developing a robust methodology for testing of electrical properties and (iv) preparations of various material compositions for the testing. Thereafter the research will direct towards the most promising fields.

Testing the withstand ability to electric degradation is a challenging task. It has been chosen to be performed by evaluating the resistance to degradation by electrical treeing. Summary of the work is presented in the following part of the paper.

MATERIAL CONCEPTS TO BE TESTED

Nanocomposites are emerging materials with extremely promising dielectric properties potentially useful as HVDC insulation materials [1]. Our approach is to have control of the synthesis of the nanoparticles (e.g. metal oxides) in order to produce uniformly sized particles (typically sized between 20 and 60 nm) with well-defined surface structure and with a minimum of counter ions. The latter is important in order to minimize ionic conduction in the composite material. The nanoparticles are coated with conventional (but well-controlled) methods e.g. by silane chemistry or by more novel polymer grafting (ATR polymerisation). The purpose is also to chemically bind functional groups on the nanoparticle surfaces (e.g. stabilisers). Important characteristics of the synthesized nanoparticles are uniform size distribution, very low ionic content, hard-agglomerate freedom and uniform coating structure. Such fillers tend to be readily distributed in polymer matrices to obtain for the application suitable nanocomposites. Parallel to this work, studies using other strategies are tested (Fig. 1). Voltage stabilizers have proven very efficient in increasing the treeing inception AC voltage [2,3]. Different strategies will be tested with regard to voltage stabilisers including both dispersed voltage stabiliser and voltage stabiliser chemically bound to nanoparticle surfaces. Even the most perfect insulation may contain voids. During the course of service such defects can be 'healed' by the migration of polyethylene-like additives.

WIRE-PLANE TEST OBJECT

Electrical treeing is one of the main degradation processes of polymeric insulation in high voltage cables. Electrical trees originate at points with highly divergent electric fields, e. g. at surfaces of contaminants, protrusions, voids or at tips of water trees. Several ways of initiating and growing electrical trees have therefore been developed to study the phenomenon. All of them utilize a sharp geometry of the high voltage electrode required for

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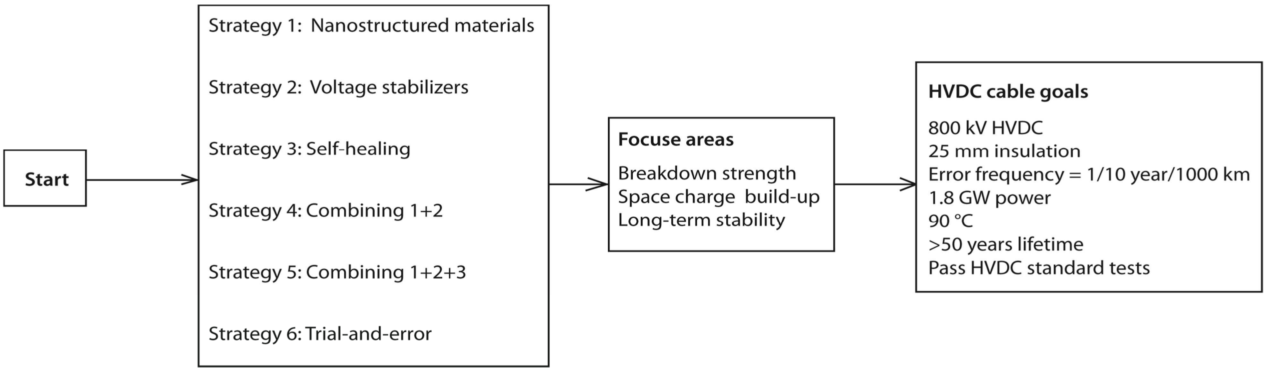

Fig. 1: Scheme outlining the project goals and the strategy for approaching the goals

creating the highly divergent electric stress and include various modifications of needle-needle or needle-plane object geometries [see for example 4-8]. Despite of an extensive use, some concerns about efficiency of such objects still remain. One concerns formation of micro-voids that may be formed close to the tiny needle tip. The tip may also fracture during the inserting process. Both the effects yielding the inception of electrical treeing process at lower voltage level than in the voids-free or fracture-free conditions. Another concern refers to the very limited contact region between the needle tip and the polymeric material (tip radius is 1-5 µm), as the treeing process is forced at the tip and not in the weakest material spots.

A new type of test object of wire-plane geometry to evaluate the electrical treeing in polymeric materials has been proposed [9,10] to simplify the sample preparation process as well as to improve the confidence of the experimental evaluations. Instead of the needle electrode, it makes use of a thin tungsten wire attached to a semiconducting tab for generating the highly divergent field in the surrounding polymeric material. Recently this idea has been developed further by removing the semi-conducting tab [11], which allowed to further reduce the time needed for sample preparation and is suitable for preparing test objects of both thermoplastic and crosslinked materials. The wire-plane configuration solves some of the problems of the needle method. While the tree formation is forced in the needle tip, the wire electrode allows to expose a larger volume of the tested material, yielding a parallel formation of several trees in the naturally weakest spots of tested material. The wire geometry is also less vulnerable during the sample preparation and the main benefit is seen in a possibility for using it during screening tests comparing electrical tree inception voltage in different materials.

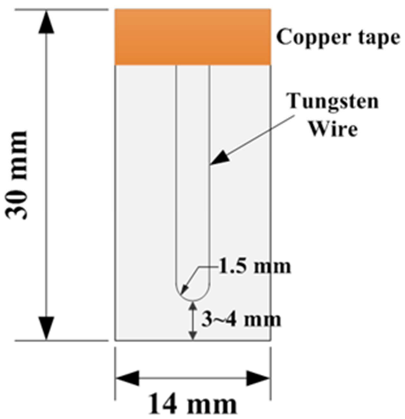

Fig. 2: Test object without semiconducting tab.

Fig. 2 illustrates the schematic diagram of the test object without semi-conducting tab. It consists of a tungsten wire embedded between two sheets of the polymeric material, connected directly to an externally attached copper tape. Here the copper tape is used as the voltage connection. The wire-plane distance is ~3-4 mm. The used diameter of tungsten wire is 10 µm. The preparation process consists of several stages. The material is first grounded, thereafter follows a melt-forming of thin plaques. Later on, the wire electrode is placed between two plaques. Objects are ready for cross linking of the polyethylene material. A microscopic check of the samples is finally performed to assure that defected samples are eliminated.

For proving the effectiveness of the newly developed object type a comparative study was made that involved 4 different types of test objects, further on denoted as A, B, C and D, as illustrated in Fig. 3.. The objects of type A and B are needle-needle, manufactured following the ASTM D3756 – 97(2010) guidelines [6].The preparation procedure of the objects has been made as consistent as possible with respect to material handling, thermal history and degassing procedure. All the objects investigated in this study have been made with commercial high voltage insulation grade cross linked polyethylene (XLPE).

Testing of electrical tree initiation voltage in the compared test objects was performed at room temperature under 50 Hz AC voltage ramping scheme with a ramp rate of 500 V/s in a container filled with transformer oil. Initiation and growth process of the electrical trees was optically detected by a CCD camera for the analysis. A detail description of the obtained results are presented in [12].

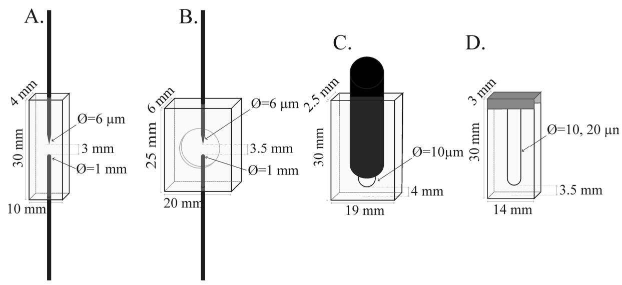

Fig. 3: Four differet types of compared objects

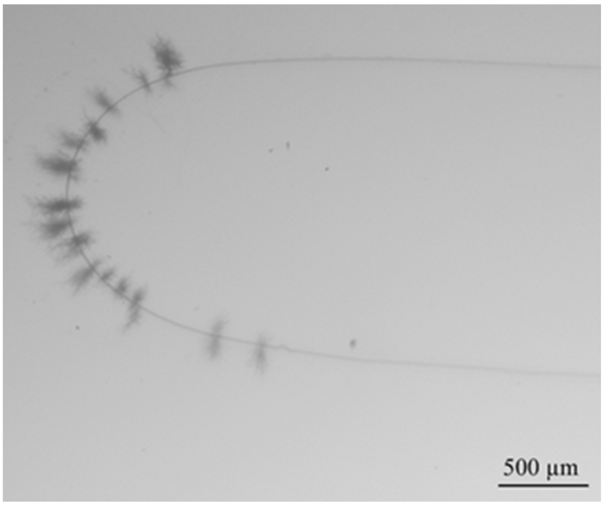

Fig. 4: Appearence of electric trees in test object without semiconducting tab

Anyhow, the main benefits of using the wire-plane geometry include the formation of multiple trees in each test object and a larger volume of material being tested, which in turn results in more data for analysis. The trees grow at different locations along the wire electrode, as illustrated in Fig. 4.

In the objects without semi-conducting tab more trees are formed along the wire electrode. To verify that the electrical tree initiate at equal conditions, independent of location on the wire, the tree inception voltage is shown in Fig. 5 for various position of their appearance in objects with wire diameter of 10 µm and 20 µm. As can be seen in the figure, the inception voltage appears to be evenly distributed, independent of location for all positions from 0° to 90°.

One may state in summary that the main benefits of this object type are that several data points are generated in per object and that a larger volume of material is tested. The removal of the semiconducting tab from the object facilitates manufacturing simplicity, increases reproducibility of results and reduces the necessary level of test voltages. An interesting aspect with this new approach is that the tree inception is not forced at one specific location but at material weaker spots, which provides an opportunity to further explore the influence of material structure.

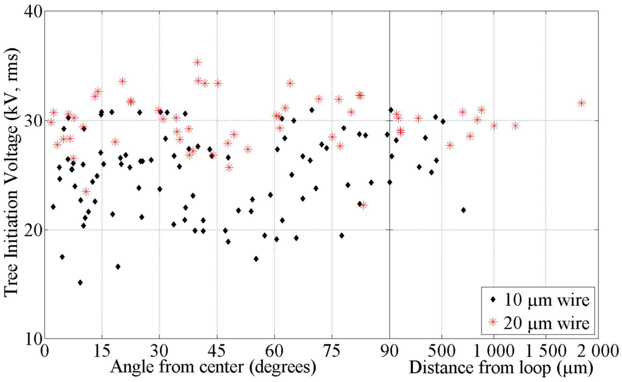

Fig. 5: Tree inception voltage with respect to location on the wire in objects without semiconducting tab

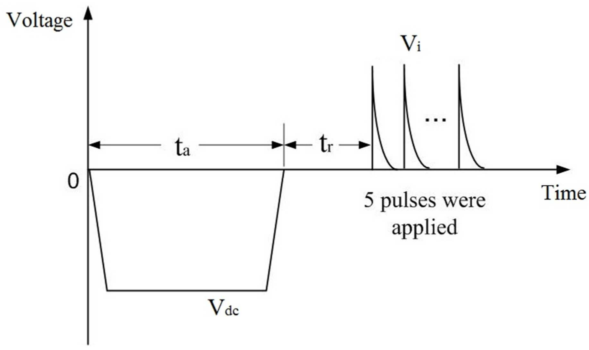

Fig. 6: Test procedure used for DC electric tree initiation

TREEING UNDER DC STRESS

DC electrical trees behave differently from AC ones and various methods for initiation have been utilized and the following methods have been established for their initiation [13,14]. These methods are summarized in the following.

1) Ramping DC voltage method - applying a linearly increasing voltage on the sample.

2) Short-circuit method - pre-stressing the sample with a constant DC voltage for a fixed time period and then immediately short-circuiting it after turning off the voltage.

3) DC pre-stress plus impulse method - pre-stressing the sample with a constant DC voltage (V_d) for a fixed time period (t_a), turning off the voltage and leaving the sample open circuited for a rest time (t_r). Thereafter applying an impulse or a series of impulses (amplitude V_i) having the same or opposite polarities to the pre-stressing DC voltage,

4) Superimposed DC and impulse method - Pre-stressing the sample with constant DC voltage (V_{dc}) for a period (t_a), and then superimposing an impulse or a series of impulses (V_{im}) on the DC voltage. Similarly as above the DC voltage and the impulse voltages may either have same or opposite polarities.

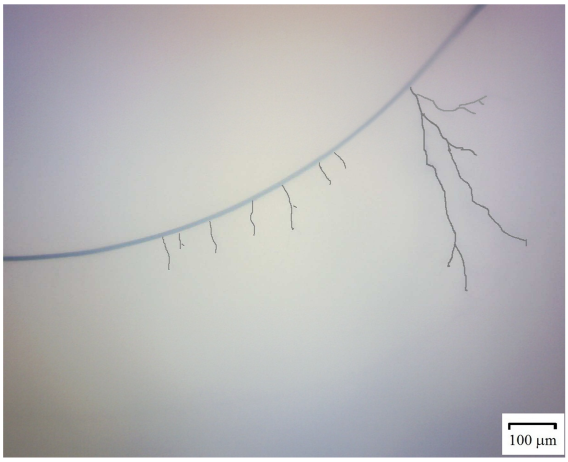

Fig. 7: Microscopic appearence of DC electric trees

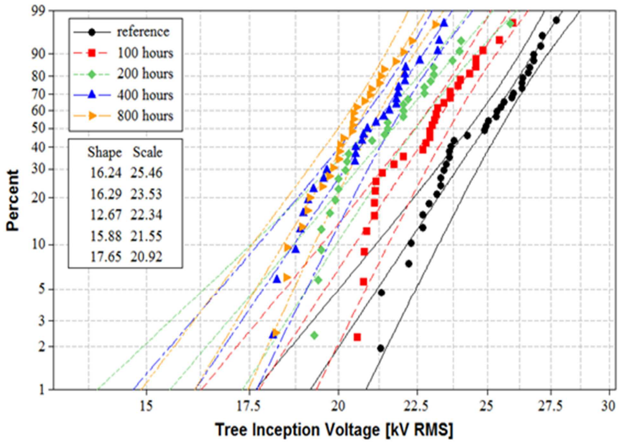

Fig. 8: Weibull plots of electrical tree inception voltage of LDPE material aged at 80℃ and -10 kV DC at different ageing times

After checking all the four alternatives, the negative DC pre-stress plus positive impulse method, as illustrated in Fig. 6, appeared to be the most effective. The parameters used were as follows: negative DC pre-stress voltage V_{dc} = 45kV, pre-stress duration t_a = 40min, rest time t_r = 2min, amplitude of the positive impulse voltage V_i = 40kV. Five impulses were applied after DC pre-stressing, having front time 1.5 µs and tail time 70 µs. The time interval between adjacent pulses was 5s. Fig. 7 shows a microscope photo of electrical trees obtained in this type of test.

EFFECT OF THERMAL AND DC ELECTROTHERMAL AGEING

This part of the work concentrated on investigating the effects of prolonged thermal and DC stresses on the electrical treeing behavior of test objects manufactured of a low density polyethylene (LDPE). For comparison, some experiments were also performed on samples made of cross-linked polyethylene (XLPE). The ageing was performed at 80℃ with 10 kV DC voltage of both polarities and lasted up to 800 hours. Before the ageing started, all the objects were degassed in vacuum at 55℃ for 7 days.

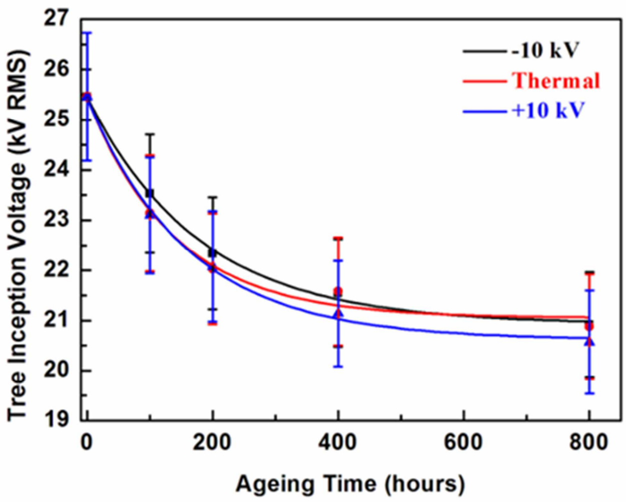

Fig. 9: Variation of tree inception voltage of LDPE material with increasing ageing time

AC treeing characteristics

Changes in the ability to withstand electric tree formation were first evaluated by testing under AC voltage. An example of the variation of two-parameter Weibull distributions of electrical tree inception voltage for LDPE material is shown in Figure 8. The distribution plots gradually move to the left with the increasing ageing time, indicating a reduction of the tree inception voltage by about 20% from 25.5 kV for the references to 20.9 kV for the 800 hours -10 kV electro-thermal aged samples. Similar shifts were found for the objects aged under positive polarity as well as exposed only to the thermal treatment.

Fig. 9 shows a summary of the obtained results for the LDPE material, where the scale parameters are plotted against the ageing time. It is seen that an evident decline of the tree inception voltage occurs up to 200 hours of the ageing, then the decay proceeds slower. At the same time, the differences between the thermally and electro-thermally aged objects remain insignificant within the error range. With this conclusion in mind and in order to confirm the dominating role of the thermal stress on the tree inception properties in polyethylene, thermally aged XLPE test objects were also evaluated. Figure 10 shows the resulting Weibull distributions showing that, similarly to the ageing results of LDPE material, the tree inception voltage decreases consistently with the increase of the time of the treatment. At the same time, the tree inception voltage generally remain at a higher level for XLPE material than that for LDPE.

The mechanisms responsible for the observed significant reduction of the tree inception voltage include morphological changes at the wire-polymer interface and eventual modifications of chemical constituency of the material, for example by consumption or diffusion of antioxidant agents. These should also affect the electrical properties of material, including its conductivity. Evidences for increase of conductivity in XLPE during thermal ageing were presented in [15] and [16], explained by weakening of molecular bonds, an increase of free volume and the resulting change of charge carriers mobility. However, the conductivity measurements performed on the used LDPE material at 70℃ and 30 kV showed a decrease by about 60% from ~2□10^{-13} S/m in the un-aged state to ~7□10^{-14} S/m after the thermal ageing. This could mainly be attributed to the diffusion of the antioxidant during the thermal treatment.

DC treeing characteristics

The objects made of XLPE material were also tested for withstand electrical treeing by means of the DC pre-stress plus impulse method. As the thermal stress applied during the ageing appeared to dominate the degradation process, the DC tree inception tests were performed on two groups of the material, each of them containing ten test objects. Group 1, being the reference group, was only degassed. Group 2 was in addition aged at 80℃ for 200 h, the same duration of aging time that yielded most of the change in the AC treeing tests.

As the online inception of DC trees was not possible in this case, the objects were investigated afterwards under a microscope. Number of the incepted trees as well as the length of longest tree were registered. Fig. 11 illustrates results of these analyses on the investigated groups. As

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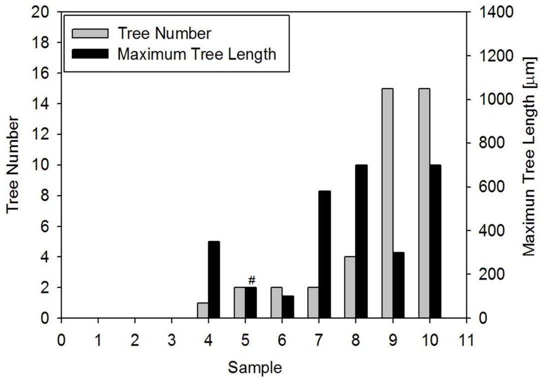
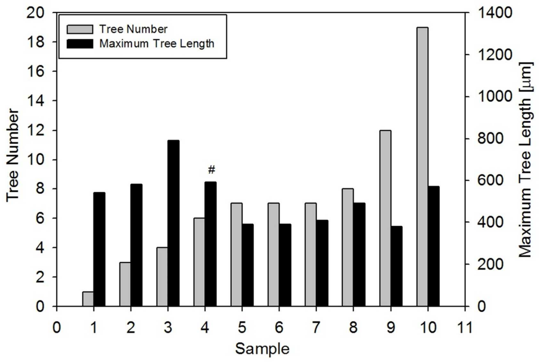


Group 1



Group 2

Fig. 11: Number and maximum length of DC trees incepted in in reference (Group 1) and aged (Group 2) test objects

can be seen from the figure, DC tree filaments were found in all the objects of Groups 2, while in Group 1 the trees appeared only in 7 objects. The largest number of trees appeared in one of the samples of Group 2, where 19 trees were incepted randomly along the tungsten wire. However, 17 of them were single-branched short trees with their lengths ranging from 40 µm to 100 µm.

Though a clear explanation concerning the inception mechanism of DC electrical tree is still missing, it is believed that formation of space charges plays here an important role. As a homo-charge is injected into the material from the electrode, to trigger electrical tree under DC voltage one has to overcome the space charge effect on the locally acting electric field. All the DC tree inception methods described above are based on this idea. Therefore the parameters of the test procedure influence strongly the obtained results. More details on this subject can be found in [17]. In particular, the level of negative pre-stress voltage V_{dc} controls electron injection. In our experiments, DC trees could not be incepted in samples of Group 1 at V_{dc} lower than 40 kV.

Similarity between results of DC and AC treeing tests

Although the morphologies of trees formed under DC and AC conditions are different, some similarities of a general type can be found between the results of both the tests. For example, Group 1 samples show stronger resistance to electrical tree inception under both DC and AC voltages. More samples developed DC trees in Group 2 than in Group 1 (10 vs. 7).

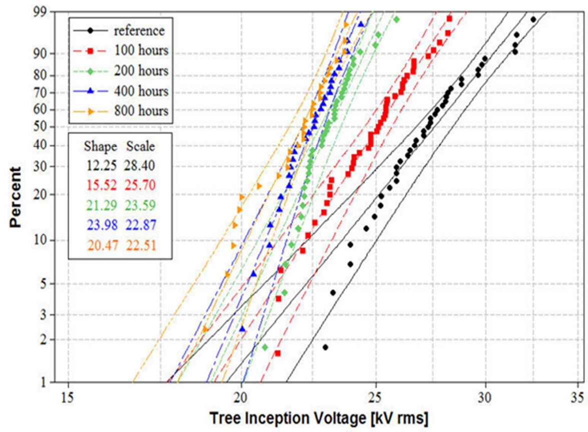


Fig. 10: Weibull plots of electrical tree inception in thermally aged XLPE material at different ageing times

As regards the AC results, Group 2 shows a lower α value than Group 1 (23.6 vs. 28.4, see Fig. 12).

At this point one may also refer to the recently published results on the effect of low frequency voltage on electric tree formation during AC testing [18]. The experiments were performed at frequency range between 0.1 and 50 Hz and showed a similar tendency as observed in the reported here work, i.e. the structure of initiated trees changed from bush-like to branch-like with decreasing frequency, while at the same time the growth rate of the observed trees (the experiments were conducted under constant voltage of 14 kV on objects with needle - plane electrode geometry) decreased significantly. No trees could be initiated under exposure of the objects to DC voltage, being blocked by the injected space charge.

CONCUSIONS

Thermal ageing of the tested materials tends to weaken their ability to resist DC treeing tests, similarly as also observed in the results of AC tree inception tests.

As the number of material compositions to be tested in the above described project is to be very large, it is postulated that the use of the AC ramping test can be included as a robust screening methodology when ranking the resistance to degradation in the new generations of materials for application in HVDC cables.

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