Close and Return

Analysis of Multiple Electrical Trees Incepted at Wire Electrode Test Object by Means of PD Detection

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ABSTRACT

This paper introduces a method allowing characterising the growth of electrical trees in wire-plane electrode objects. By applying both electrical and optical measurements the inception level and the number of trees were analysed. It is shown that the results observed optically closely resemble the electrically detected PD behaviour, thus exhibiting a good correlation between both the methods. This indicates a possibility for analysing electrical treeing process in non-transparent materials based on the electrical measurement only and opens for an efficient approach in evaluating new materials for cable insulation.

KEYWORDS

Electrical treeing, PD detection, XLPE, voltage stabiliser

INTRODUCTION

In parallel with the in Sweden ongoing research activities, aiming to deliver new materials for applications in high voltage direct current (HVDC) cable insulation (intended for voltage levels up to 800 kV), several concepts are being evaluated. One of these considers the possibilities provided by the use of insulation containing voltage stabilizers. The work presented in this paper focuses on development of a robust test methodology for evaluating the resistance to electrical treeing of different material candidates. The work aims at enabling monitoring of the treeing processes in semi- or non-transparent material samples, in which the widely used optical detection is not easily applicable. This method is based on measurements of partial discharge (PD) activity that accompany the tree initiation and growth [1, 2] in test objects with wire-plane geometry under exposure to a ramped AC voltage. The use of wire electrode objects provides several advantages as compared to the conventional needle electrode configurations, mainly by allowing a larger volume of the investigated material to be exposed to the highly divergent electric field, which subsequently results in a formation of multiple trees [3]. To facilitate the diagnostics, statistical methods are applied for characterizing the PD activity.

TEST METHOD

The electrical treeing tests have been performed using a test set-up comprising a transformer allowing for voltage ramp rates between 20 and 160 V/s, a voltage divider and a PD measurement system. The latter is based on the principles described in [4, 5] and it allows to follow the development of PD activity in the electrical tree channels. This method has been chosen due to its efficiency in separating the PD signal from the applied voltage, while only requiring use of simple electric components. By using the PD decoupler in parallel to the test object instead of in series with it protects the set-up in case of the occasional

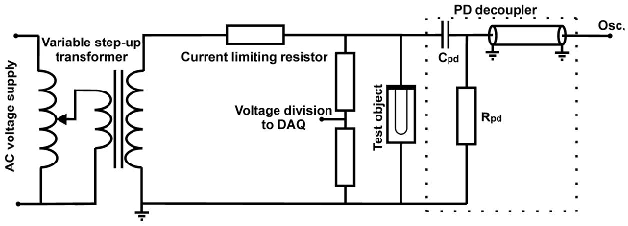

Fig. 1: Electrical test set-up with the PD decoupler

breakdown in the test objects. Fig. 1 shows the used electric test circuit. The PD decoupler comprises a 95.66 pF capacitor, C_{pd}, a 51 Ω resistor, R_{pd}, as well as a 1.80 meter long coaxial cable with the screen grounded at both ends. The resistor and capacitor create a high pass filter suppressing the applied sinusoidal voltage without affecting the high frequent PD signal, and the coaxial cable acts as a resonant amplifier for the high frequency components of the signal, thus increasing the PD amplification. The PD detector is connected to a Tektronix DPO4000 oscilloscope with 8 bits resolution and a bandwidth of 350 MHz. Data traces containing one period of the applied sinusoidal voltage are collected at a 50 MS/s and stored. After approximately 1.7 s the system is ready to record the next signal trace. The testing has been performed for three different 50 Hz AC voltage ramp rates: 20, 80 and 160 V/s.

The optical detection of the treeing process is made by means of a stereomicroscope coupled to a CCD camera and is used here as a reference for relating the PD activity to the tree inception, recording 3.7 frames per second at a resolution of 2048 x 1532 pixels. This allows detection of trees smaller than 10 µm for accurate determination of their initiation. The electrical tree initiation tests were performed at ambient conditions with test objects immersed in transformer oil in a custom made container as shown in Fig. 2.

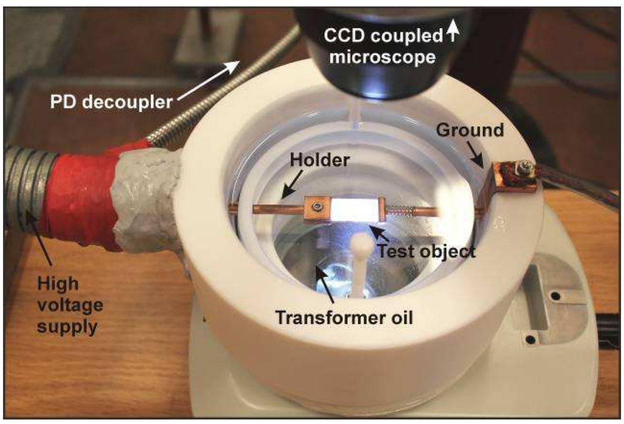

Fig. 2: Test set-up showing the microscope coupled to a CCD camera and the test object holder

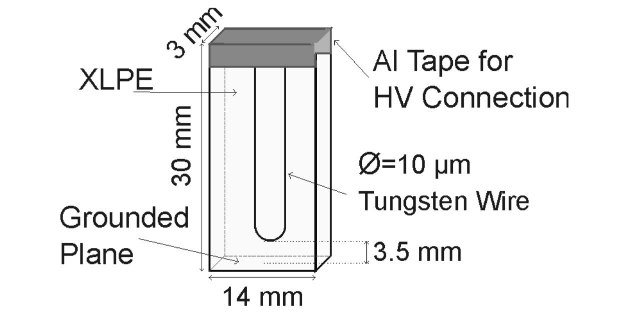

Fig. 3: Design and dimensions of the wire-plane test object

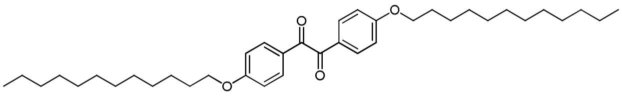

Fig. 4: Chemical structure of the added stabiliser "4,4'-didodecyloxybenzil"

A detailed geometrical design and dimensions of the test objects used in this work is illustrated in Fig 3. Premade pieces of polyethylene are joined together while the wire electrode is placed in between them. First the whole assembly is melted in a special mould placed in a hot press at 130℃ and 2 kN for 15 min and thereafter both the pressure and temperature is increased to 200 kN and 180℃ for cross-linking during 15 min. After cooling down to ambient temperature, the objects are degassed at 80℃ in vacuum for 5 days. In the final step they are heated again to 130℃ and left to cool down overnight for ensuring an equal thermal history between different batches.

A high voltage cable grade polyethylene, with and without addition of a newly synthesised voltage stabiliser, "4,4'-didodecyloxybenzil", was used for this evaluation. A concentration of 10 mmol/kg of the stabiliser was added into the polyethylene. The chemical structure of this voltage stabiliser is illustrated in Fig. 4.

STATISTICAL PROCEDURE FOR PD DETECTION

In order to improve the signal-to-noise ratio in the PD traces a statistical method is applied on the stored data, even though 50 Hz sinusoidal test voltage is sufficiently suppressed. To minimise the influence of noise and to allow the detection of weaker PDs an accumulated sum is first calculated and thereafter removed from the measured signal according to Eqs. 1 and 2, as introduced in [4].

$$u_{acc}(t,c-1)=\frac{u_M(t,c-1)+nu_{acc}(t,c-2)}{n+1} \quad [1]$$

Here u_M denotes the measured signal, u_{acc} is the accumulated sum from the earlier signal traces and n is set to the number of traces chosen for averaging. c is the cycle number and t is time. For the tests presented in this work n was set to 120 when applying the voltage ramp rate of 20 V/s and to 20 for the faster ramp rates, in which the voltage remnant varied more between two consecutive traces. The calculated sum, u_{acc}, is then removed from the measured signal according to Eq. 2.

$$u_{diff}(t,c)=u_M(t,c)-u_{acc}(t,c-1) \quad [2]$$

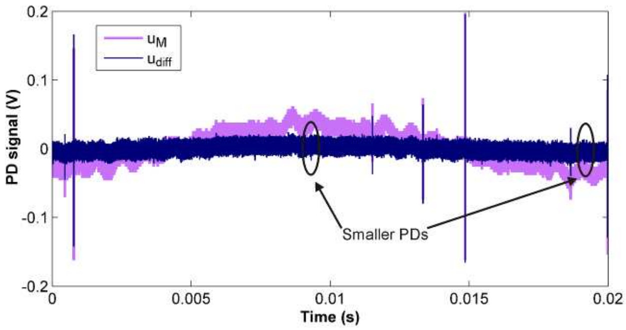

Fig. 5: PD trace before and after averaging; two smaller PDs are highlighted

u_{diff} denotes the difference between the captured voltage trace and the accumulated sum from the previous recorded traces. Due to the stochastic nature of the PDs both phase-locked disturbances and the remnant from the applied voltage are reduced. Fig. 5, displaying u_M and u_{diff} illustrates how the low frequency contributions from the applied voltage are removed and also how the signal-to-noise ratio is somewhat improved as illuminated by the highlighted peaks. U_{diff} is then employed in detecting the individual PD amplitude and phase position by using a simple threshold value of the peak-to-peak voltage set to 0.035 V. This approach is based on the acquisition principles used in [4, 5] and has been implemented in a LabView based software.

RESULTS

Accuracy in PD detection of the first tree

To facilitate for future studies on non-transparent insulation materials the previously applied optical methods [3] are to be complimented and correlated to an electrical detection of the treeing processes. In real-time the optical and electrical detection seemed to be simultaneous, however when evaluating the optical recordings frame by frame these proved to show tree inception slightly in advance of detectable PD signals, i.e. above the noise level. This difference in voltage level, between the optically detected tree inception voltage and the voltage level at which a first PD can be observed is illustrated by the box plots in Fig. 6. These data include the detection of the first tree in each test object for the different investigated ramp rates.

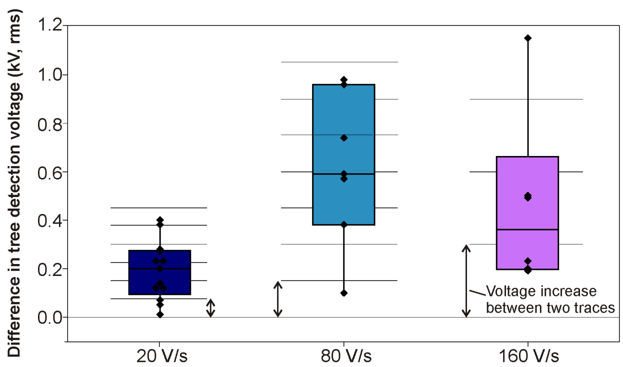

Fig. 6: Box plot showing difference in detected tree inception voltage between the optical and electrical detection method for the first tree in each test object for the different voltage ramp rates

The voltage level where the first tree is optically detected is set here as zero voltage level and the difference between the first detected PD and this voltage is plotted in the figure both as raw data and fitted to a box plot, with the mean and the 75 percentiles indicated. Further the increase in voltage between captured cycles is indicated by the grey lines. As the time between recorded traces is constant, 1.7 s, the difference in applied voltage is larger for the higher ramp rates. As can be observed, the slowest ramp rate has the least deviation and scatter between the optical and the electrical detection of tree inception voltage, with a mean value of the difference at around 0.2 kV and a maximum deviation slightly higher than 0.4 kV. This is a satisfactory agreement between the two methods as the variation in tree inception levels for individual trees is significantly larger. For the intermediate voltage ramp rate the difference in detection levels becomes larger, both concerning the mean value and the deviation. This could be attributed to the variation in applied voltage steps between the PD traces and the different averaging weights used for the statistical process of the data as described above. However another cause could be related to the fact that trees at the higher ramp rates generally initiate at higher voltage levels and thus also grow more rapidly, probably producing stronger PDs from the beginning. For the fastest ramp rate this trend is similar, though a limited number of data makes further analyses inadequate. In conclusion it can be noted that the ramp rate of 20 V/s produces the smallest error between the electrical PD detection and the optical detection of the tree inception voltage, still all tested voltage ramp rates can be used for good detection of the first tree.

Relating the PD activity to the inception of further trees

As the ramp rate of 20 V/s resulted in the highest accuracy, further investigations concentrate on this particular case. To elucidate how the PD activity relates to the treeing process some different parameters have been considered to utilize the obtained information. The selected parameters are: the number of PDs, the maximum, the aggregated and the average PD amplitude. Each of these parameters is calculated per sinusoidal period. However, as the number of PDs provided the most interesting results, these are in focus in the following.

The progress of a typical treeing process along the wire is illustrated In Fig. 7, showing similar tendencies of degradation as observed in all the tested objects. The inception of each new tree together with the extent of growth of the previous ones is seen in each picture together with the corresponding initiation voltage. To simplify the following analysis only the first five trees are considered. The corresponding raw data of number of detected PDs from the same test object are shown in Fig. 8 and reveal a considerable scatter, which complicates a coherent analysis. The chosen method to simplify this analysis employs a calculation of floating mean values, according to Eq. 3.

$$PDnum_f(i) = \frac{PDnum(i) + nPDnum_f(i-1)}{n+1} \qquad [3]$$

The variables are assigned as follows: *PDnum* is the number of detected PDs, $PDnum_f$ is the floating average and *n* is the weight, here set to 6. The variable *i* corresponds to the PD trace number. This floating average is also plotted together with the raw data in Fig. 8. To facilitate the comparison between electrical and optical detections, the inception voltage for each of the five trees is indicated on the x-axis in Fig. 8. Based on this representation one can conclude that an apparent change in the number of observed PDs is strongly related to the appearance of another electrical tree. This is further stressed by observing the characteristic slopes of PD number increase for the first four trees in the figure, with noticeable changes in the steepness as new trees appear in the test object.

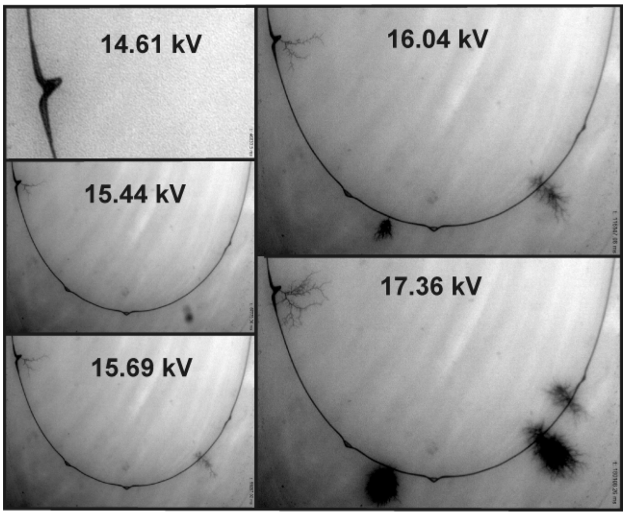

Fig. 7: Tree inception voltage of the five first trees along the wire also showing the extent of growth in the previous trees

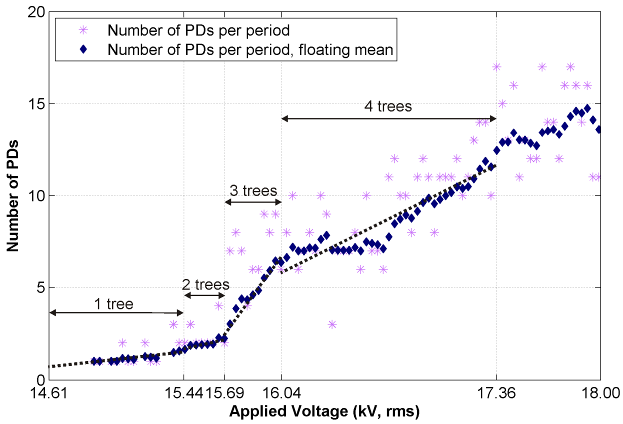

Fig. 8: Number of PDs per cycle, for the test object illustrated in Fig. 7. The slopes of this parameter are indicated with straight lines for different characteristic regions where one, two, three and four trees are growing. Note that the x-axis mirrors the tree initiation voltage levels for the different trees.

The presented approach to identify changes in the number of growing trees has been utilized on all test objects. Fig. 9 shows the variation in the steepness of the slope for the first three trees. It can be noted that the slope increases with the number of trees, though the spread increased also. A tendency for an increase in the number of detected PDs as well as in the slope suggests that the presented analysis constitutes a promising method for determining the initiation and the quantity of

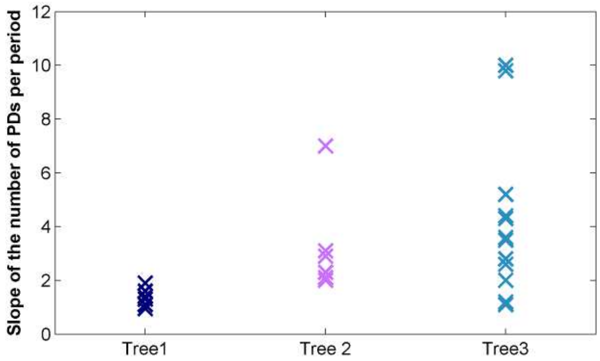

Fig. 9: Slope of the number of PDs per period for the first three trees appearing along the wire electrode

electric trees in insulation. Further these parameters are likely to depend on the voltage level and the stage of the growth of already existing trees.

Number of trees and influence of stabiliser

So far the gradual changes in PD characteristics have been evaluated for a limited number of trees. In this section the data are accumulated and compared after completion of the tests, including all the incepted trees. Analyses are made for the different ramp rates as well as for both the reference and the stabilised XLPE. First of all, the general tendency shows that the number of PDs per period is linearly correlated to the number of trees present in the objects, as shown in Fig. 10. As seen the objects tested at a faster ramp rate resulted in slightly lower level of detected PDs per period. On the other hand, when comparing the different materials, no significant variation is visible. A linear fit to all the data is included and it is further utilised to recreate the tree inception voltage from the PD information.

As previously shown [6], adding voltage stabilizer increases the resistance to electrical tree formation. Thus, when evaluating different materials, this effect should also be reflected in the information provided through PD analyses. To enable such comparisons, it is preferable to use an approach where the results of analyses are presented in Weibull statistics plots. Here the optical measurements of the inception voltage level for the first four trees are fitted to a 3-parametric Weibull distribution, similarly as in [3]. As a first approximation, the data for the four trees observed optically are compared with the electrical results for five trees, assuming that a few have

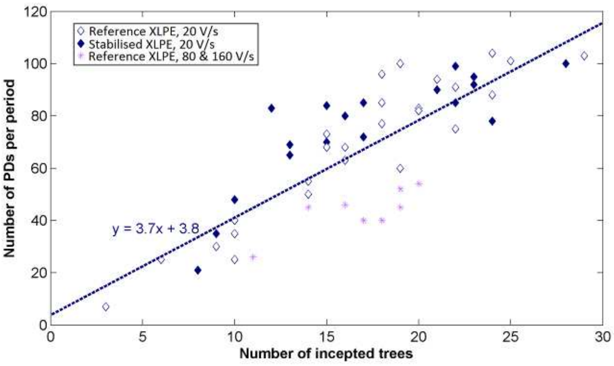

Fig. 10: Number of PDs detected versus the number of incepted trees when test is completed for both materials. This data is fitted to a linear function.

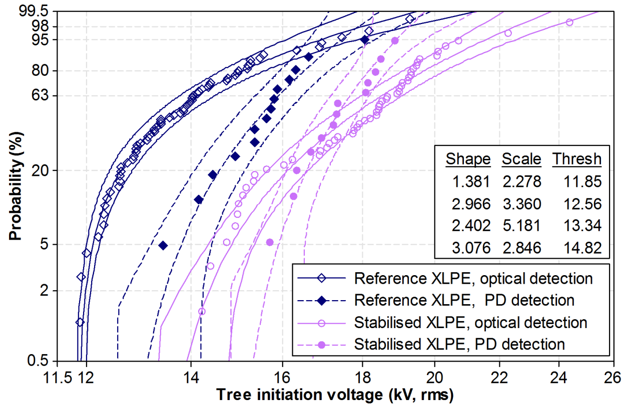

Fig. 11: Three-parametric Weibull fit of tree initiation voltage for the two materials compared. Fits are presented for both the optical data and from the PD measurements.

originated from defects. In the latter case, it is assumed, based on the approximation from Fig.10 that 22 PDs per period are by average corresponding to the formation of five trees. The voltage level at which this number of PDs are detected is retrieved as the tree inception voltage of the investigated test objects. Three-parametric Weibull distributions from both the optical and the proposed electrical detection method of test series for the reference as well as the stabilised material are illustrated in Fig.11. As can be observed the stabilised material shows higher resistance to electrical treeing and this behaviour is also reflected in the PD data, as expected. This suggests that the electrical approach can be employed to evaluate different materials based on the electrical measurements only.

CONCLUSIONS

A good correlation has been observed between the results of electrical detections based on PD measurements and the optical observations of electrical trees incepted in polyethylene based materials under 50 Hz AC ramped excitation. In particular, the change in the number of detected PD events as well as the PD amplitudes provides information about the ongoing degradation process. As the main goal of this work has been to allow efficient characterization of non-transparent materials; the presented method has indeed shown a great potential. It is illustrated here by comparison of the resistance to electrical treeing in XLPE materials with and without addition of voltage stabiliser.

Acknowledgments

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GLOSSARY

PD: Partial Discharge
XLPE: Cross-linked Polyethylene