Detection of electrical tree propagation by partial discharge measurements

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Abstract — The partial discharge activity during propagation of electrical treeing in epoxy resin is described. The electrical trees grew in needle-plane samples without and with an internal barrier up to the final breakdown. The simultaneous taken tree growth and discharge activity show a correlation between the propagation state of the tree and the thereby measured PD. Especially the changes in the tree structure can clearly be detected. Based on these characteristics a new model describing tree growth will be presented. It appears that measurements from machine insulation can be interpreted in terms of the PD pattern.

1. Introduction

Partial discharge (PD) measurement techniques for electrical machine insulation have been improved in the recent years. Although PD measurements are widely used detailed interpretation of the PD in terms of defects and degradation in the insulation material has still not been completely clarified. The PD data show stochastic oscillating behaviour with periods of low and periods of higher amplitude [1] - [4].

During their service the mica-epoxy winding insulation may be exposed to PD and electrical treeing for long periods. The electrical treeing, a process in which fine erosion channels propagate through the material, is often referred to as the most important degradation mechanism in solid polymeric insulation [5] - [9]. In this the electrical treeing can start at rough structures of the inner conductor, locations of abraded outer varnish, metallic particles or other conducting contaminants, gas-filled voids or delaminations in the insulation.

Although much work has been done in the field of electrical treeing (a comprehensive collection is given in [5]), complete descriptions are only given for tree inception and partly for tree growth with only intermittent PD measurements [6] - [9]. A complete investigation of treeing and the thereby generated PD up to the final breakdown has so far not been given.

In order to evaluate the tree growth in winding insulation the electrical treeing has been continuously recorded from tree inception to the final breakdown by taking optical analyses of the tree growth and simultaneous PD measurements. The experiments were carried out in samples with and without mica barriers. An analysis of electrical treeing, the size of the channels created and their PD will be given and the existing models of tree growth will be extended.

The PD characteristic of the electrical treeing in point-plane specimen has been compared to that measured on actual high voltage coil winding insulation. Similarities and differences of the PD characteristics will be pointed out.

2. Experimental setup

The experimental arrangement is mainly a conventional PD test circuit consisting of a 5 kVA, 50 Hz high voltage power transformer, a 1:1000 capacitive voltage divider, a 700 pF coupling capacitor with a coupling impedance and a phase resolved PD measurement system (PD Tech Switzerland). The PD measurements were taken with a recording time of 60 s of each pattern. The treeing experiments were carried out with needle-plane specimens with a constant ac voltage of 28 kV RMS. To promote treeing from the beginning of the voltage application, needles (Ogura Jewel) with a tip radius of 1 µm were used. The relatively large distance of 5 mm between the point and the plane was chosen to study tree growth in a wider volume considering the higher insulation thickness of high voltage winding insulation. To simulate the effect of barriers in the insulation, square mica plates of 20 mm length and a thickness of 0.2 mm were placed centrally between the two electrodes perpendicular to the axis of the system. The electrical treeing was observed with a CCD-camera via telephoto lenses.

For simultaneous measurements of the electrical tree growth and the generated PD thereby, the camera and the PD measurement system were controlled of one and the same PC (Figure 1).
The test samples, 40 mm by 40 mm by 40 mm in size were fully moulded in epoxy resin (relative permittivity of 4.0) of type Araldite D (Vantico). For easy detection of the trees a fully transparent formulation was chosen. High voltage was applied to the needle. The plane surface of the sample opposite the needle tip was coated by conducting silver paint and grounded.

3. Electrical tree propagation from inception to breakdown

A. Electrical tree growth without a barrier

The tree growth was evaluated by subdividing the images into squares of 100 um length in the space between the needle tip and the plane. The length of the tree was then determined as the straight distance from the needle tip to the line of the furthest tree branch. Therefore 100 % of relative tree length means that the first branch reached the plane electrode.

Due to the high electric field at the needle tip the inception of the first branch (minimum length of 100 um) occurred during the initial voltage rise to the final value. In all samples tested the tree inception time was less than 30 seconds. Once the first branch had been created, the electrical tree grew in small branches to the ground electrode (Figure 3). That growth follows basically the shape of a “lying S” (Figure 2). The mean time for the first branch to reach the opposite electrode was 14 min. Taking the distance between the needle and the plane this means a mean growth time of 2.8 min/mm.

When the first branch reached the plane and bridged the electrodes the breakdown did not occur. It is therefore assumed that the small branches have such a low conductivity that the current flow is insufficient to cause the breakdown.

The size and structure of the small branches were investigated with a visible light microscope. The small branches have an internal diameter of less than 10 um in the trunk and less than 1 um in the very thin tips (Figure 6). Although in the literature branches are considered as hollow [5], the present microscope analyses do not confirm this. The branches seemed to be filled up with decomposition products of the polymer caused by the tree growth itself.

After the first branch has reached the opposite electrode, more branches will be created and more volume between the needle tip and the plane is taken up by the tree (Figures 4 and 5). Parallel small parts of the existing branches will be widened and their structure changes to small hollow pipes. Those pipe-shaped channels have a diameter of larger than 10 um, with typical values between 60 um and 150 um (Figure 7).

The mean value of the total breakdown time of the measured 10 samples is 60 min. The time the tree needs to bridge the electrodes (14 min) is therefore only 24 % of the total breakdown time. This means for the insulation material that even if no breakdown occurs the tree may already have penetrated it (Figures 3, 4 and 5).
B. Electrical tree growth with a mica barrier

In composite winding insulation the tree usually grows around the mica barriers between the inner and outer conductor [10]. To simulate this, a mica plate was introduced centrally between the two electrodes. Due to applying the same voltage and needle tip geometry the tree inception takes place as described in section 3.A. Because the tree can not grow through the barrier, the branches propagate around it to the opposite ground electrode (Figure 8).

The mean time for the first branch to reach the ground electrode was 150 min. Compared to the time found without a barrier (14 min), this means a prolongation by one order of magnitude. This is assumed to be due to the fact that the tree must take a longer way around the barrier and its branches spread on the surface of the barrier in order to find the most favourable way to the opposite electrode. Taking into account that the tree crossed the barrier mostly along the shortest path (10 mm), the distance the tree takes around the barrier from the needle to the ground is total 15 mm. This means a mean growth time of 10.0 min/mm (treeing without barrier 2.8 min/mm).

The mean value of the total breakdown time of the measured 10 samples was 257 min. The time the tree needs to bridge the electrodes (150 min) is therefore only 58 % of the total breakdown time. That means, similar to the samples without a barrier, even if no breakdown occurs the tree may already have penetrated the material (Figure 8).

As well as in the samples without a barrier the small branches will be widened up to pipe shaped channels once they reached the opposite electrode. The size of the first branches as well as the size of the widened channels are about the same to that without a barrier (section 3.A), (Figure 6 and 7).

C. 3-stage tree growth model

The existing tree growth models give a detailed description for the inception and for the growth of the trees but only until the first branch reached the opposite electrode [5]. Considering the measured tree growth characteristics in epoxy resin (section 3.A and 3.B) this appears incomplete. On the basis of the results a new 3-stage tree growth model was derived (Figure 9).

Stage 1 is considered to be the tree inception. This stage will not be explained further in detail because it is detectable only by very sensitive measurements that are not practicable within electrical machines.

Stage 2 is considered to be the growth of the first small branches to the opposite electrode (Figure 2). It starts at tree inception and it ends when the first branch has reached the opposite electrode. The branches are characterised by a size < 10 um in the trunk and < 1 um in the tip (Figure 6).

Stage 3 is considered to be the stage where the small branches will be widened up to a pipe shaped structure. It starts when the first branch has reached the opposite electrode and it ends with the final breakdown. The channels are characterised by a size of > 10 um having typical values between 60 um and 150 um (Figure 8).

4. Partial discharges during propagation of the electrical tree

A. Partial discharges at the growth of small tree branches in stage 2 of the model

The growth of the small tree branches (stage 2 of the model) is mainly determined by local solid breakdowns in the epoxy resin. The branches with diameters < 10 um cause only low discharges between 5 pC and 30 pC (mean value of apparent charge). Occasionally maxima up to 300 pC may emerge (Figure 10, where the mean values are indicated by the wide bars and the highest and lowest measured values are indicated by vertical lines).

In discharge experiments with small microcracks it has been measured that the PD inception at voltages of 28 kV occurs in spherical cavities of minimum 50 um diameter [11]. Possible discharges in the small tree branches may therefore be retarded due to their narrowness. Supposing that those branches are filled with decomposition products of their creation, it is assumed that this causes the remaining low PD during phase 2 of the model although there are many small branches bridging the electrodes (Figures 3, 12 and 13).
B. Rise of partial discharges with change of tree channel type in stage 3 of the model

The pipe-shaped tree channels in stage 3 of the model have a diameter of >10 μm with a medium measured length of >0.5 mm. Those channels cause discharges between 50 pC and 220 pC (mean value of apparent charge). Occasionally maxima up to 2500 pC may emerge. The PD in the big channels have a very stochastical and oscillating character with higher amplitudes (Figure 11, where the mean values are indicated by the wide bars and the highest and lowest measured values are indicated by vertical lines, Figures 12 and 13).

The change of the channel type leads to the measured rise of the PD amplitude and frequency almost like a step function. From the microscopic analyses it was seen that the wider pipe-shaped channels are hollow (Figure 7). The simultaneous data recording showed that the creation of those channels does not necessarily cause a high PD. Furthermore, the hollow structure of the channels provide the basis that higher PD can occur. Whether discharges occur in those channels depends on the local charge distribution, the local conductivity of the channels and the pressure and composition of the gas that fills the channels. When there are pipe-shaped channels partly open to the ground electrode and thus to the atmosphere more and higher PD has been observed. The channels will be widened up until the first continuously hollow channel bridges both electrodes. The breakdown then occurs as a gaseous breakdown within that channel.

The characteristic behaviour of stage 3 of the model was observed quantitatively in all samples tested, not depending on having a long or a short breakdown time or having a barrier or no barrier between the electrodes.

The PD are also dependent on the length of the created channels [5]. In narrow holes of short length small discharges in a high number will be produced, whereas in holes of larger diameter and long length, higher amplitude discharges but fewer in number occur. Due to the tree is always changing its structure (in stage 3 of the model) the different types appear simultaneously. Therefore it is important to record the apparent charge as well as the maximum apparent charge. Such behaviour will be illustrated by a short (epoxy without barrier in Figure 12) and a long (epoxy with mica barrier in Figure 13) treeing- and therefore breakdown time.

The step-like change of the PD between stage 2 and stage 3 of the model mentioned above leads to a sharp bend in the curve representing the cumulated charge (Figure 14 with the two samples with and without a barrier). The sharp bend might be used to detect the degradation state of the material when the tree changes its structure from stage 2 to stage 3.

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From the tree growth model it can be seen that the detection of the treeing state in the material is most likely within stage 3 starting when the channel type changes from stage 2 to stage 3. Therefore the PD-pattern created in stage 3 has been analyzed. The pattern measured during tree growth in stage 3 of the model can be characterized by an almost triangular shape with a highest slope tending to be near voltage zeroes (Figures 15 and 16).

5. Partial discharges in rotating machine insulations

Partial discharge on- and off-line testing is part of quality assurance and preventative maintenance programs. It helps to determine the actual condition of rotating machine insulation and its components. Testing allows to prevent losses due to unforeseen and undetected faults.

The insulation of rotating machines is subjected to combined stresses, thermal, electrical, ambient and mechanical (team) that all affect the integrity of the machine insulation and cause defects with partial discharge activity.

On-line partial discharge measurements provide important information about the progress of insulation degradation under operational conditions or identify defects that are excited by operational stresses e.g. vibration, temperature and load dependent problems in motors and generators. Therefore, this gives the user greater in-sight into the condition of the apparatus, which is not usually accessible with normal off-line testing methods. Often insulation failure and detectable ageing are caused by non-electric processes, as overheating magnetic cores, defects in the mechanical support structure or pollution. Insulation problems are most often not the origin but the result of these problems. Therefore, partial discharge activity is generally an indicator for such macroscopic injury of the insulation. The appearance and characteristics of partial discharge patterns relate to specific defects within the test objects. This will be shown by comparing the patterns of the PD as follows.

Main insulation discharge activities are characterised by triangular patterns with a highest slope near voltage zeroes (Figure 17). Physically they are mostly as a result of discharge activity within layers of partially delaminated insulation where the electrical treeing takes place.

End-winding discharge activity are characterised by semi-round patterns with the highest slope near the voltage maximum (Figure 18). Physically they are mostly caused by a deficiency of field grading materials where their pollution results in PD in the end-winding region.

The sparking and burn-off of the semiconductive layers are characterised by a pattern, which is more of an oval shape with a highest slope near voltage rise (Figure 19). Physically they are mostly caused by the defects in end-winding layers that cause the external portions of the semiconductive coating to be burnt off. This can lead to serious discharge activity between the insulation surface and the core that lead to a destruction of the outer coatings (Figure 20).
3. Conductive because they may penetrate the insulation and must not be considered to be continuously electrode. These branches have diameters of some um branches from inception until they reach the opposite stage 2 represents the electrical tree growth in small practicable within electrical machines.

4. Stage 3 represents the electrical tree growth in small branches from inception until they reach the opposite electrode. These branches have diameters of some um and must not be considered to be continuously conductive because they may penetrate the insulation without causing breakdown. Due to the narrowness of the branches, discharges of only some tenths of a pC occur that makes their detection in electrical machines difficult.

5. Introducing a mica-barrier between the electrodes prolongs the total breakdown time of the samples.

6. Partial discharge measurements on machines allow identification of defects that may lead to breakdown. These defects can be classified by its PD-patterns. The patterns measured during discharge activity in the main insulation are of the same type as those measured during the electrical tree growth in the samples of epoxy resin.

7. Although the PD measurements of epoxy samples show a correlation between PD and the degradation state of the material, a detectable residual life criterion must be further developed because different mechanisms leading to PD in machine insulation must be considered.

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