Andrzej Sierota

ON THE PROBLEMS OF TESTING OF RESISTANCE OF SOLID DIELECTRICS TO BREAKDOWN RESULTING FROM PARTIAL DISCHARGES

1. Introduction

Solid synthetic polymers, when exposed to high electric field stresses show irreversible and accumulative changes of degradation which lead to ultimate breakdown.

The major mechanisms of degradation are due to partial discharges (PD) and to electrical treeing (ET) however, in both, the ionisation phenomena play the dominant role in development of the failure process.

Due to great improvement of technology a specific deadlock on the field of testing of different dielectrics from the point of view of their resistance to PD can be recently observed. At the same time, the experimental data regarding comparative studies of, either the rate of degradation or resistance to degradation, remain controversial and show lack of practical interpretation. The further attempts towards evaluation of the method of testing of the resistance against different degradation processes are still substantial.

2. Scope

The existing experience from aging tests indicates that the most adequate methods for studies of effects of degradation of different materials by PD are those, related to statistical, accelerated breakdown test in different model arrangements. So far, very different types of ar-

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Dr. Andrzej Sierota - Institute of High Voltages, Warsaw University of Technology, Poland

rangements have been used for such studies.

There are numerous examples of voltage tests carried out in open-type electrode-sample arrangements with gaseous gaps between dielectric - dielectric or metal - dielectric electrodes however, life tests have been done in the open arrangements with surface type discharges [1,2,3].

During studies of the author some arrangements with internal type PD were mainly adopted. Their choice was associated with particular type of so called "degradation source" in the real insulation, which means macroscopic or microscopic (not structural) inhomogenity or fault existing in insulation due to design, technology or service conditions.

The "classical" arrangements with internal PD are with a void, either embeded in the volume of dielectric or adjacent to a metal electrode(VA).

In this paper the problems o modelling and testing of degradation by means of artificial arrangements have been extended thus, slit arrangements (SA) with discharges between two dielectric layers, as well as needle arrangements (NA) with discharges developing tree-like channels are also considered.

3. Sources of degradation in insulation

The faults in dielectric materials can be specific for different types of insulating systems and, therefore, two separate parts of problems should be derived contributing to degradation of dielectrics in: a)cast, extruded, crosslinked, moulded, injection moulded insulations, b)laminated, impregnated, composite insulations.

In the paper only the bulk type materials used for a) type indoor insulations are taken into account.

It can be briefly reported after the analysis of some data available that the most often identified faults are due to technology of processing either of a material itself or of insulating system [4,5,6,7].

The most often identified faults in insulation are:

- gaseous voids (regular bubbles, spheres, semi-spheres also cracks) inside of the material or in a contact with electrodes,

- gaseous slits (narrow, widely spread) between dielectric surfaces or adjacent to a metal parts,

- contaminations (conductive and non-conductive solid particles).

The size of acceptable imperfections can be drasticly reduced by the improvement of technology thus, a size of gaseous voids can be of single μm, tens of μm, sometimes houndreds of μm, and a size of contaminations from single μm up to tens of μm [5,6,7,8]. Presence of gaseous slits was sometimes identified in insulations after their processing or mounting and also during the service [4,7,9].

Many other kinds of allowable technological defects have been mentioned in some references like: cracks, chips, blisters, pumples, pits, pinholes, spots, etc. However, there are also some faults appearing due to long-term physical processes in insulation which lead to crack (epoxy)or void (polyethylene) formation [9,10]. Such faults can act as degradation sources as well.

4. Modelling of degradation sources

Different faults either in extruded or cast insulations represent, in fact, different damaging effects. Thus, no single mechanism can describe the process of destruction of insulation. Similarily, no single model arrangement can reflect all possible risks of degradation resulting from PD.

Experimental work done by some researchers showed that during aging tests with various dielectrics in different model arrangements, the dominant degradation mechanisms (PD and ET) can display themselves together in a complex way [11,13,16] being generated either on the boundary or inside of the solid phase. This indicates that also the methods of testing of resistance against degradation should be related to: a) surface, b) volume respond of the dielectric when affected by discharges [14]

In the studies of the author three different types of model arrangements were proposed to be used for testing of resistance of dielectric materials against degradation by PD representing the above mentioned main degradation sources in insulation. Similiarity of both: real and artificial systems does not necessarily mean their geometrical correspondence but rather simulates some common physical features in the mechanism of failure i.e. of type of degradation.

(a). Void arrangement (VA) simulates the source of internal, nonextinguishing PD developing in sealed and limited gaseous volume where gas decomposition and variations of gas pressure take place. PD initiate erosion process of a void surface and also localisation of discharges at particular sities of a void takes place. Pre- breakdown tree-like channels developing from localised points of the void are due to local intrinsic breakdown in the front of channel tip and (or) due to degradation by PD in the channel, leading to final breakdown [15,16].

(b). Slit arrangement (SA) consists of gaseous void and gaseous slit. Internal PD are initiated in the void and then spread into slit forming surface type discharges resulting in surface tree-like degradation traces over both parts of sample. They develop due to high potential of the tree tip maintained by discharges in a channel and (or) by the electrical conductance of channel. The final breakdown path across the dielectric is the extension of one of pre-breakdown channels [17,18].

(c). Needle arrangement (NA) represent particular type of degradation initiated by field enhanced emission of electrons and (or) electron bombardment, resulting in creation and enlargement of microvoid or microcrack. When the gaseous phase is large enough (>1 μm) PD occurs developing tree like breakdown channels until final failure [19,20]. Regarding a particular type of insulation different sets of model arrangement were proposed [14,21,22]:

- for testing of resins VA (or SA) and NA,
- for testing of polyethylene SA and NA.

The choice of models was not quite arbitrary as the analysis of failures either in epoxy or polyethylene systems justifies such selection. However, it can be said, that the presence of all faults in a real insulating systems simulated by three above arrangements is unlikely with advanced, of high level technology.

In the all arrangements adopted the attention has to be paid to the assessment of the model "purity" and reproducibility. Several parameters have to be regarded in the model, as: geometrical dimensions (electrode's spacing, void geometry, slit geometry radius of curvature of electrodes); gas-dielectric and metal-dielectric boundary state (surface roughness of voids and slit, contact of the dielectric and electrode); residual mechanical stresses. Preparation of both parts of a model: dielectric sample and electrode, should always introduce a controlled manufacturing process, suitable methods of examination and criteria of selection of faulty specimens.

Due to different type of VA, SA and HA arrangements the problems of their preparation should be considered separately. They were reported elsewhere by the author [23,24]. Another important problem emerges from the reproducibility of the structure of samples and their similiarity to the structure of the real insulation.

It is understood that the same, controlled technological process has to be applied to provide the same morphology however, either during casting of resins or extrusion or moulding of polyethylene many factors exists to make the control difficult. It may results in modification of morphology of apparently identical samples [25,26,27]. The problem of morphology of the sample for resistance-against - degradation tests have not been solved yet however, some attempts are being made towards definition of polyethylene sample [28].

5. Assessment of test conditions

When the resistance to the ultimate effect of degradation by PD ought to be evaluated the measurements of time to breakdown of definied sample size are required.

For comparative breakdown tests quantitative results are mainly required thus. There is tendency to simplify the test procedure and to limit the number of specimens tested.

There is no general definition of sample size for testing of resistance to breakdown due to degradation except of some reccomendations given for testing against ET and surface discharges [3,29].

Thus, in many cases, the sample size can be reduced and the minimum number of n = 10 has been often accepted [29,30] for testing of different materials, their fillers, additives etc. However, in order to provide a statistical approach to the test results and also statistical criteria of testing the sample size should be large enough and, therefore, a great deal of samples have to be manufactured for every test.

According to the author's experience manufacturing of large set of repeatable samples of any kind can be very laborious and difficult [23, 24]. On the other hand, reduction of sample size causes lack of certainity of the results obtained thus, a reasonable compromise should always be found. In the tests carried out by the author the sample size of n=10 was always used for primary testing and the results were verified with n=25 or n=30 [14,22,31].

One of the most difficult decissions which have to be made to establish the test conditions is the most informative electrical stressing. It must be not too low to initiate a degradation process and its effects in reasonable period of time and, at the same time, not too high to avoid the change of mechanism of degradation, as the life curves of various systems (also artificial arrangements) can change their slope with rising of the stress [32]. The accelerated test conditions accept, however, the test stress levels which are above the working stresses.

There is also accepted for comparative laboratory voltage life tests that a test stressing should be determined experimentally to provide resonable duration of test [29]. With particular type of the model adopted such stressing can be changed either by the test voltage level at constant dielectric thickness or by electrode separation distance at constant voltage.

In VA the test voltage from 20 kV to 40 kV and dielectric thickness from 2 mm to 5 mm reported in different references [15,16,32], give the stress variations possible from single kV/mm up to about 20 kV/mm. The same conditions can be created in SA though, according to the author, lowering of the dielectric thickness down to 2 mm in VA and to 1 mm in SA with the test voltage of 20 kV to 25 kV does not significantly change the character of degradation of these systems in comparison with conditions existing for working stresses providing, at the same time, tolerable long time of testing [31,42].

In NA dimensions of sample were once unified either for single or double needle (or SPINGS) systems [29,34].

With the critical voltage of about 20 kV possible to be applied to such sample and the recommended distance between electrodes from 2 to 6 mm, the average stresses (accross the gap) are from about 3 kV/mm up to

10 kV/mm however, the field enhancement factor (i.e. the effective voltage stress) due to tip radius of needle electrode is responsible for the rate of degradation.

Recently, OGURA cone-shaped needles with tip radii of simple µm were widely accepted for needle tests. Some of results reported [30] showed that for comparative tests of resistance to electrical breakdown by ET reduced values of dielectric thickness (around 2 mm) can be assumed. Such conditions enable shortening of time of testing up to few - several hours and it was also confirmed by the experiments of the author [14,22,31]. Such reduction of duration of testing is always required in particular, in simplified laboratory tests. Some of requirements say that the test conditions should enable to obtain the results within 24 hours. This applies to divergent field voltage life tests of polyethylene materials with the reduced sample size n=10 i.e. according to [29].

For breakdown of epoxides much longer time is usually required. In VA and SA there is often impossible to provide the stress conditions which enable such limitation of duration of the test [16,31,33]. As it was reported earlier a high degree of responsibility and purity of samples permits the execution of shortened (cut-down) tests in which only limited number of samples (i.e. i=7 with n=30) have to be broken down [14,22].

6. Presentation of test results.

Although normal or Weibull statistics have been mainly accepted to produce breakdown tests results and to provide statistical criteria of testing, in some recommended sources more simplified method has been used to express the resistance to electrical breakdown as the time required for 50% of specimens to fail (t_{50}). Such approach is accepted in the divergent field voltage life tests [29]. However, in order to formulate a more universal approach when different model arrangements are used the results of all tests should be presented similiarily, with respect to the statistical rules. The t_{50} criterion enables a great deal of simplification but, should rather not be used for presentations of all: VA, SA and NA test results as, at the present stage, the general concept still requires wider verification and acceptance. Thus, the Weibull distribution can be used to enable statistical and physical interpretation [35,36].

The results can be given graphically (squares method) or computed (maximum likelyhood method, linear estimation method) and scale parameters t_{63} (full-size test) or t_{20} (cut-down test) with censored number of samples can be evaluated to express the resistance of various materials to electrical breakdown by different degradation processes.

The results of tests done by the author according to the above proposed method were presented elsewhere. They aimed at qualitative comparison of different types of EP, PMMA, LDPE, XLPE materials and the influence of filters, antioxidants, additives etc. [14,21,22,23,24,31,41,42].

7. Conclusions

In the paper some of problems of testing of resistance of organic solids to breakdown resulting from different types of PD were outlined.

The resistance to PD was expressed by the characteristic parameters of Weilbull distributions of results obtained during accelerated tests with continiously applied voltage to the different, repeatable and selected model arrangements with so called "degradation sources". The test results showed that the models adopted can select different materials qualitatively however, the sequence of the characteristic time to breakdown t_{63} or t_{20} can be different for different arrangements [14,22,41].

It indicates clearly that the materials can react in different manner to various types of PD thus, such procedure of testing can reveal the difference in intrinsic and surface property (both morphological) of the solid media.

Many sources stated that surface and volume structure of semicrystalline organic solids can differ greatly and in fact, no homogenous morphological state ever exists in moulded piece of polyethylene material as amorphous phase in surface layer is dominant, changing to more crystalline contents versus distance towards depth of the moulded piece [37].

Also the state of each cast profile of many resins reveal two-phase agglomerate structure with certain number, size and distribution of agglomerates having different molecular weight with cross-linked density and being a function of distance from the surface of individual cast [38].

As the resistance to degradation by PD can differ in VA, SA and NA arrangements used, the meaningfulness of the results has to be carefully regarded and related to the most damaging or the most frequent effects in the real insulation in respect to its technology and service conditions.

There is obvious that the evaluation of the long time behaviour of synthetic solids at the presence of PD can be done not only according to breakdown tests at constant voltage level. An approach based on measurements of the residual strength of voltage pre-stressed samples in VA was once proposed [39]. It reduced scatter of results and demonstrated a significant reduction of electrical strength by PD.

Concerning NA (single or double) some other (also standarized) concepts of characteristic voltage tests revealing fraction of specimens showing initiated treeing, of divergent-field voltage tests, as well as of treeing resistance tests under stepwise increased, stress (tree inception test) were also accepted [40]. Another method of breakdown test with already initiated trees after stepwise treatment was used by the author [41]. Also other methods were applied in the past.

As it was mentioned earlier only needle arrangements were widely accepted for the standarized testing of the resistance to treeing however, they do not simulate the all possible effects of existence of different faults. Their only use can be fully objective when very small imperfections of single μm in size are only present in insulation. With an average level of technology this can not be justified.

There are some other data indicating that the evaluation of damaging effects of PD either on the surface or inside of dielectric by application of different methods (e.g.microscopic, mass spectrometry, IR photometry, X-analysis TSC, and others) can, to some extend, predict the behaviour of dielectrics exposed to PD thus, their ability to withstand such damaging effects as: surface erosion, void or cracks formation, prebreakdown channel development.

The usefullness of such methods have been recently extensively examined by many researchers [43].

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