Weibull Statistics In Electrical Aging of Polyesterimide Under AC Voltage

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ABSTRACT: This article is aimed at the investigation of electrical aging of polyesterimide under AC voltage using Weibull statistical analysis. It's shown that the time to breakdown characteristic (*V–t*) of polyesterimide includes two zones (segments of straight line). The first zone characterizes a statistical dispersion of the intrinsic defects of material. The second zone expresses the real aging of polymer. The variation of the slope of lifetime curve is attributed to the change in the degradation mechanism. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 116: 1593–1596, 2010

Key words: polyesterimide; electrical aging; failure; Weibull statistics

INTRODUCTION

The use of polymers in electrical equipments should not be missed nowadays thanks to their electrical and mechanical properties as well as their availability. However, due to the different stresses to which they are subjected in service, these polymers can be degraded and could lose their good electrical and mechanical properties. The level of this degradation depends on many parameters such as the environment, the applied voltage (wave shape and amplitude), and the time during which this voltage is applied. The degradation in time (called "aging phenomena") of the electrical properties up to the breakdown of solid materials is characterized by irreversible deteriorations affecting their performances and their lifetime. The introduction of defects during the implementation of polymer and/or the manufacturing of systems also influences significantly the lifetime of insulating systems. These defects called "youth defects" can be either solid impurities or cavities. The application of voltage can induce local enhancements of the electric field at these defects resulting in the initiation and development of partial discharges that can lead to the partial and/or total deterioration of insulation (i.e., chemical modifications of material and change of the electrical and mechanical properties).[1–3] The analyze of the mechanisms of degradation by partial discharges in solid insulating materials has been the subject of numerous studies.[4–8] The goal of such investigations is to well understand the processes implicated in the degradation mechanisms to improve the properties of existing materials or to conceive best ones and to ensure the reliability of electrical equipments for a long time. According to the different results reported in literature, the degradation of polymers is achieved according to the three stages that can be summarized as follows[9]:

1. During the first stage, very fast discharges occur within a cavity that is known as streamer-like discharges.
2. In the second stage, the discharge mechanism changes. This change is due to a very thin layer of oxidation products resulting of discharges attack at the dielectric surface. This surface gets a substantially lower resistivity and contains more electrons in shallow traps, so that electron avalanches within the cavity can easier be formed. When this layer is formed, the discharge mechanism changes into a slower type which is known as Townsend-like mechanism.
3. During the third stage, there is a formation of crystals. The discharges concentrate within cavities at some of these crystals and get a character reminding the corona discharges. At the spots where these discharges concentrate, a severe deterioration of the dielectric occurs. After some time, the discharges concentrate more and more on a few spots resulting in a severe deterioration of the material and to the initiation of an electrical tree at one of these spots leading to breakdown.

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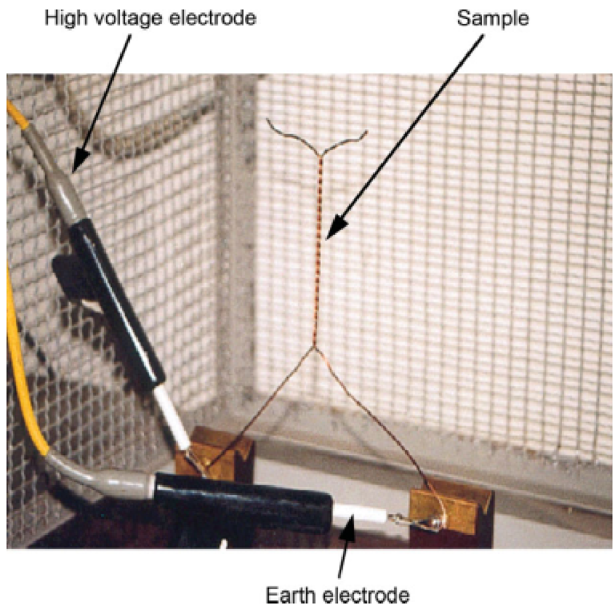

Figure 1 Photograph of experimental setup representing a polyesterimide sample and the electrode connections. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

This article is aimed at the study of electrical aging of polyesterimide under AC voltage; this polymer is used in electrical machines such as motors, generators, and transformers. The time to breakdown was analyzed by the two-parameter Weibull distribution.

EXPERIMENTAL PROCEDURE

The samples consist of twists of copper wire covered with a 35 μm polyesterimide layer of class H (180°C). The copper wire coil insulated by polyesterimide of grade 2 was supplied by "TREFUCUIVRE" company (Algerian manufacturer). The diameter of wire and the length of twist are 0.75 and 125 mm, respectively. To avoid presence of any microscopic cracks, which can constitute the site of partial discharges, the samples are checked under a microscope before the tests.

Two copper bars, in which the dimensions are 2000 × 20 × 5 mm, were deposited on a wood support. They were separated by a distance of 150 mm. The first bar is used as high voltage electrode and the second as ground electrode. The samples were placed as follows: the two conductors of each twist were linked to the first bar and the other two conductors to the second bar, respectively. These bars were connected to a transformer (16 kV, 50 Hz). The device can receive several specimens. The whole is placed in a Faraday cage. Figure 1 illustrates a sample under electrical aging.

The tests were performed in air and at ambient temperature. The cumulative time to breakdown is measured using a stop watch. To perform reliable statistical analysis, a population of 50 samples was subjected to aging at the desired voltage.

RESULTS AND DISCUSSION

Statistical analysis of time to breakdown

The dielectric breakdown is a random phenomenon.[10,11] To predict the lifetime of insulation systems, several statistical models are used, and one of the widely employed model for statistical analysis of the time to breakdown the solid insulation is Weibull model.[12,13] In the following we will use this kind of distribution. The cumulative probability $P(t)$ generally used to treat the values of time to breakdown t obtained from the life tests, is the two-parameters Weibull distribution which is given by the following equation[14]

$$P(x) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad (1)$$

where α is the scale parameter representing the time to breakdown for a probability of 63.2% and β is the shape parameter representing the slope of the straight line of Weibull plot.

The experimental data plot must be a straight line, the slope is β in the coordinate system

$$X = \log t \quad (2)$$

$$Y = \log\left(\ln\frac{1}{1-P}\right) \quad (3)$$

where P is the cumulative breakdown probability.

The measured values of the time to breakdown are plotted according to the two- parameters Weibull

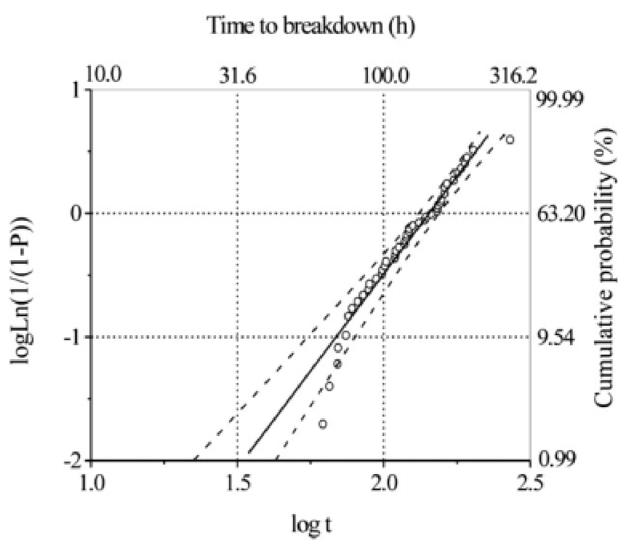

Figure 2 Weibull plot of the time data to breakdown with 90% confidence intervals at 1 kV.

TABLE I
Values of the Nominal Time and the Shape Parameter

Voltage (kV)	Nominal time α (min)	Shape parameter β
1	$7895.52 < \alpha = 8573.28 < 9268.56$	$2.520 < \beta = 3.148 < 3.717$
1.5	$2341.44 < \alpha = 2616.96 < 2805.90$	$2.521 < \beta = 3.524 < 4.161$
2	$1052.94 < \alpha = 1103.46 < 1157.64$	$4.321 < \beta = 5.385 < 6.349$
2.5	$649.02 < \alpha = 684.66 < 720.30$	$4.008 < \beta = 5.025 < 5.941$
3	$422.16 < \alpha = 448.92 < 476.94$	$3.344 < \beta = 4.148 < 4.973$
3.2	$252.72 < \alpha = 277.08 < 304.38$	$2.203 < \beta = 2.746 < 3.238$
3.5	$144.52 < \alpha = 159.88 < 175.95$	$2.054 < \beta = 2.565 < 3.028$
3.8	$56.44 < \alpha = 67.98 < 81.10$	$1.114 < \beta = 1.392 < 1.643$
4	$36.45 < \alpha = 43.62 < 51.72$	$1.154 < \beta = 1.442 < 1.702$
4.2	$27.33 < \alpha = 34.97 < 44.19$	$0.841 < \beta = 1.050 < 1.240$
4.5	$7.98 < \alpha = 9.77 < 11.84$	$1.026 < \beta = 1.281 < 1.512$
5	$7.12 < \alpha = 8.50 < 10.05$	$1.174 < \beta = 1.467 < 1.752$

distribution. The experimental values of the time to breakdown are classified by ascending order (i.e., from the smallest to the largest). And the cumulative breakdown probability P_i is calculated for each time t_i by using the relationship[15]

$$P_i = \frac{i}{N+1} 100\% \tag{4}$$

where N is the total number of tested samples and i is the number of samples that failed up to and including the time t_i.

Note that a new standard (IEEE Std 930TM-2004) proposes another formula instead of eq. (4). However, in the following we will use the formula (4).

The maximum likelihood method was used for the curves fitting. The 90% confidence intervals and the parameters (α, β) were derived. The Weibull model was validated by the χ^2 test. The different steps of calculation have been described in a previous study.[16] Note that we used the maximum likelihood method because the confidence intervals calculated by the least-squares regression (another method used for the curve fitting) are much narrower than those obtained by the maximum likelihood; the use of the least-squares regression is statistically an incorrect method.[16]

Figure 2 presents Weibull diagram of the time to breakdown at 1 kV. We observe that the width of confidence intervals is more important for the lower probabilities. Table I gives a summary of the results obtained for different voltages. The values of the shape parameter vary from one distribution to another.

In the field of reliability, the risk is normally included between 1 and 5%. We choose a limit of the risk equal to 5%. The results of the χ^2 test are exposed in Table II where $\chi^2_{v,a}$ and χ^2_{cal} represent the χ^2 test deduced from Pearson's law and χ^2 calculated, respectively. We remark that in all cases, $\chi^2_{v,a} > \chi^2_{\text{cal}}$ and the test is favorable.

Lifetime characteristic

The lifetime of solid insulating materials is deduced from tests performed for long times of electrical aging. From the experimental data, the V–t characteristic representing the dependence in time to breakdown of the applied voltage in log–log scales is plotted, according to the inverse power model which is one of the most frequently used in the aging studies of solid insulation under electrical stress. It is described by the following relationship[17]

$$V^n \, . \, t = k \tag{5}$$

Then

$$\log V = -\frac{1}{n}\log t + \frac{1}{n}\log k = -\frac{1}{n}\log t + k \tag{6}$$

where t is the time to breakdown, V is the applied voltage, k and k' are constants, and n is the voltage

TABLE II
Results of χ^2 Test

Voltage (kV)	χ^2_{cal}	$\chi^2_{\text{v,a}}$	Results
1	0.44	9.49	Favourable
1.5	9.34	9.49	Favourable
2	4.80	9.49	Favourable
2.5	4.77	9.49	Favourable
3	3.24	9.49	Favourable
3.2	1.51	9.49	Favourable
3.5	1.85	9.49	Favourable
3.8	5.69	9.49	Favourable
4	2.38	9.49	Favourable
4.2	8.74	9.49	Favourable
4.5	9.48	9.49	Favourable
5	8.72	9.49	Favourable

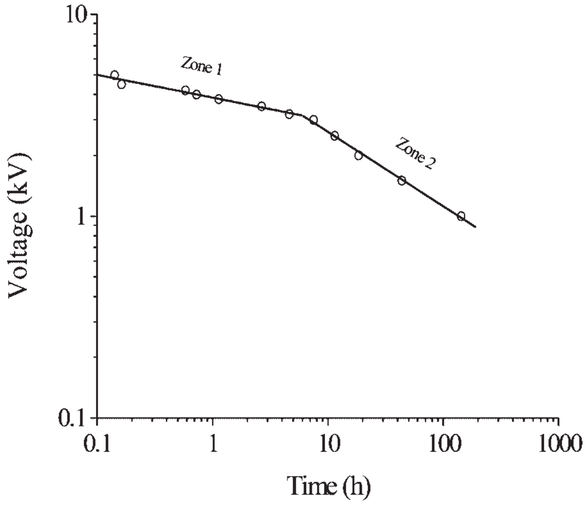

Figure 3 *V–t* characteristic of polyesterimide.

endurance constant which depends on the type of material. n is an indication of the insulation quality. To test the applicability of this model, the data are plotted in a log–log scale and checked if they follow a linear law (straight line). The slope of this latter is equal to $(-1/n)$.

Figure 3 shows the evolution of applied voltage versus the time to breakdown (63.2%) in a double logarithmic scale. This curve includes two segments of straight line (zones) whose slopes are different. These zones intersect at the point ($t = 6$ h, $V = 3.1$ kV) representing a change in the degradation mechanism. Each zone corresponds to a given type of aging. The presence of several segments of straight line in lifetime characteristic has been reported elsewhere.[1,3,18] Note that the weaker the applied voltage, the longer the time to breakdown is.

Zone I, characterized by $n = 8.92$, would correspond to a statistical dispersion of the intrinsic defects in the material according to the results reported in literature.[3,17] An intrinsic defect could be a microcavity because of a lack of control during the polymerization or to an interrupted reticulation during the crystallization process. Indeed, during the extrusion operation, impurities can be accidentally introduced into the material in a random manner. In this zone, the lifetime is expressed, according to eq. (5), by

$$t = 173637\ V^{-8.92} \tag{7}$$

Zone II, corresponding to $n = 2.65$, represents the real aging of polymer. When submitting the material to a prolonged action of the electric field, some of its physicochemical properties change in time, leading to the appearance of new defects and thence to degradation of the dielectric strength of polymer. Several processes of evolution such as oxidation and thermal degradation are possible. The distribution and the dimensions of these defects are random. In this zone, the lifetime can be written, according to eq. (5), as

$$t = 129\ V^{-2.65} \tag{8}$$

The transition from one zone to another one corresponds to a change in the mechanisms of degradation. Each type of degradation is characterized by a given value of n.

CONCLUSION

The lifetime characteristic (V–t) of polyesterimide presents two zones (segments of straight line) which intersect at a point representing a change in the degradation mechanism of the dielectric material. Each zone is characterized by a given value of voltage endurance constant. Zone I would correspond to a statistical dispersion of the intrinsic defects of material. Zone II expresses the real aging of polymer where new defects (i.e., cavities) appear. The distribution and the dimensions of these defects are random.

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