

Breakdown Behaviour of Polyesterimide Enamelled Wire Subjected to Thermal Aging

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ABSTRACT

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This work concerns the effect of thermal aging on breakdown voltage of polyesterimide enamelled copper wire. Samples are aged in ovens at different temperatures. After aging, a large population of samples were taken and submitted to dielectric breakdown under AC and DC voltages. The material was characterized by TGA and DSC. The values of failure were treated statistically using Weibull model. The study shows a decrease in breakdown voltage with respect to aging time. DC breakdown voltage is greater than AC breakdown voltage. Under DC stress, breakdown voltage is related to the polarity. TGA thermograms exhibit one decomposition stage. The beginning temperature of the mass loss and the residue are greater in the case of pure samples. The glass transition temperature decreases as a function of aging time resulting to a plasticization in the material. In long-term, the decomposition occurs by a scission reaction of imide - bond and ester - bond at interface of polyesterimide-copper. A through discuss of the obtained results is given as well.

1. INTRODUCTION

Dielectric materials of electrical machines (motors, generators, ...) is one of the most important parts of them in function of the production costs as well as the maintenance and lifetime [1].

During functioning of electrical equipments, dielectric materials are submitted to thermal aging. In long term, thermal stress induces insulation decomposition which can lead to failure. Thermal degradation causes depolymerisation, chain scission, oxidation, crosslinking, hydrolysis, etc. The various mechanisms have been reported elsewhere [2, 3]. Therefore, it is very useful to know the causes and ways to prevent fast degradations that can yield the shortening of its lifetime.

Polyesterimide is widely used in rotating electrical machines. It has an excellent resistance to high temperatures and good electrical and chemical properties [4]. For these reasons, the use of the polyesterimide enamelled wires has grown rapidly. In spite of all its advantages, several studies mentioned that this material degrades under thermal stress [5-9].

In a previous work [5], we evaluated the thermal endurance of polyesterimide. We pointed that the breakdown voltage of the polymer is reduced by aging.

Araki and Taguchi [6] reported thermal aging of polyesterimide magnet at 230°C with both copper and aluminium conductors. The results of tested specimens with copper pointed a rapid decrease in breakdown voltage with aging. In case of samples with aluminium, the decrease is not significant.

In the investigation of thermal aging of polyesterimide, Brandes et al. [7] mentioned a diminution in dielectric strength with respect to aging.

Fetouhi et al. [8] examined the permittivity and the electrical conductivity of impregnating varnish based on

polyesterimide before and after thermal aging at 240°C for 720 h. This investigation exhibits high variation of the real and the imaginary parts of the complex permittivity and in the DC conductivity of the resin after aging.

Werynski et al. [9] investigated accelerated thermal aging of polyesterimide enamelled copper wire over-coated with polyamide - imide. The samples were submitted to thermal aging at 250 and 270°C. The study shows a decrease in breakdown voltage with respect to aging at 270°C. Also, an increase in capacitance against aging at 250 and 270°C was highlighted.

The goal of this paper is to investigate the evolution of AC and DC breakdown voltage of polyesterimide enamelled copper wire submitted to thermal aging. Values of breakdown voltage were analyzed statistically using Weibull model. Physical-chemical analysis were achieved by TGA and DSC.

2. EXPERIMENTAL TECHNIQUES

2.1 Elaboration of specimens

The specimens were built as twisted conductors according the IEC 60851-5 Standard [10]. The conductor diameter and the thickness of the polyesterimide layer are 0.63 mm and 35 μm , respectively. The length of the specimens is 125 mm. The dielectric is of class H (180°C). Before exposure of the samples to aging, they were checked with a microscope for the detection of any presence of cracks.

2.2 Thermal aging

The specimens were submitted to continuous thermal aging in ventilated ovens regulated at different temperatures: 190, 210, 230 and 250°C. These temperatures were chosen to be

greater than class of the material which is 180°C. Due to the statistical nature of dielectric breakdown, measurements were realized on a large population. For each sampling, 50 samples were taken from the ovens.

2.3 Breakdown test

A ramp – shaped high voltage rising with a speed of 0.5 kV/s was applied to the specimens until breakdown occurs. The experiments were performed, in air at ambient temperature, under DC voltage with positive / negative polarity and 50 Hz AC voltage. After failure, the value of breakdown voltage was recorded.

2.4 Characterisation

The polymer was characterized by TGA and DSC before aging and after 960 h, 1920 h and 3456 h, respectively, at 210°C.

2.4.1 Thermal gravimetric analysis (TGA)

The thermal gravimetric was monitored with TGA 2050 Thermogravimetric Analyser (TA) Instruments at temperatures ranging from 30 to 1000°C under a nitrogen atmosphere. A powder was carefully taken from enamelled wire and was put in a crucible. The heating rate is 10°C/min and programmed with a computer. The average mass of the samples is 8 mg.

2.4.2 Differential scanning calorimetry (DSC)

An apparatus type 2020 Modulated DSC TA Instruments was used to perform DSC measurements on specimens in nitrogen atmosphere. To build specimens, a powder was taken and put in a capsule which was pressed. The mass of the samples varies between 5.0 mg and 5.6 mg. The tests are performed at temperature range 50-400°C. The heating rate is fixed to 20°C/min and programmed with a computer. Three scans of heating and cooling were executed for every tested sample.

3. STATISTICAL ANALYSIS

The breakdown voltage data were analysed statically using the two-parameter Weibull model. This latter is widely used in the study of dielectric rupture of solid dielectrics [11, 12]. The Weibull model is yield by the next relationship [13]:

$$P(V) = 1 - \exp \left[- \left(\frac{V}{V_0} \right)^\beta \right] \quad (1)$$

P(V): cumulative failure probability,

V: random variable, in this study represents the breakdown voltage,

V₀: scale parameter (nominal breakdown voltage) which corresponds to a cumulative breakdown probability of 63.2%,

β: shape parameter which is the slope of the straight line of Weibull curves. It is a measure of dispersion of breakdown voltage values.

The Weibull graph must be a straight line in the coordinate system:

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

$$Y = \log \text{Ln} \frac{1}{1 - P} \quad (3)$$

The cumulative breakdown probability P of each value of breakdown voltage V_i was calculated using the relationship [14]:

$$P = \frac{i}{N + 1} 100\% \quad (4)$$

N: number of specimens,
i: rank of V_i.

The breakdown voltage values were ranked by ascending order. In this investigation, number N was fixed to 50 as given before in subsection 2.2. The best linear fit of Weibull graph was established by an estimation based on the method of the maximum likelihood. (V₀) and (β) were deduced from Weibull graphs.

4. RESULTS AND DISCUSSION

4.1 Weibull graphs

Figures 1a, 1b and 1c present some examples of Weibull graphs: before and after 3456 h at 210°C.

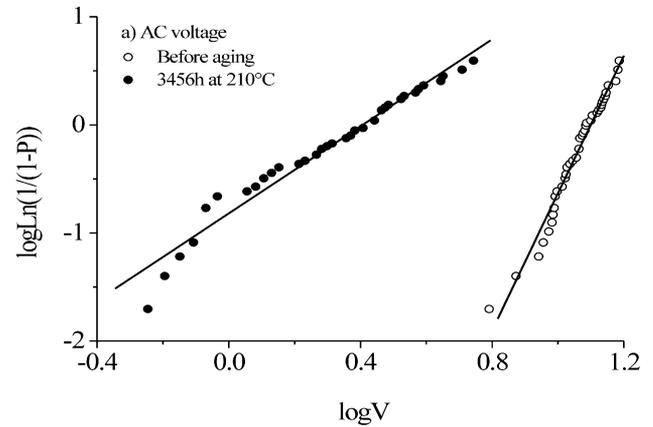


Figure 1a. Weibull graph of AC breakdown voltage
Before aging: V₀ = 12.45 kV, β = 6.75
After 3456 h at 210°C: V₀ = 2.56 kV, β = 2.00

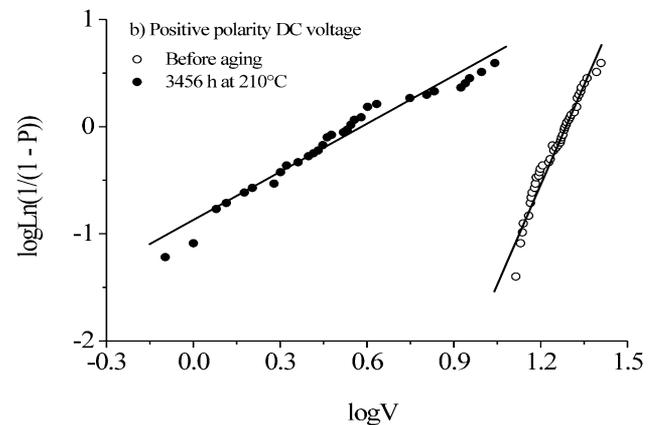


Figure 1b. Weibull graph of positive polarity DC breakdown voltage
Before aging: V₀ = 19.38 kV, β = 6.21
After 3456 h at 210°C: V₀ = 3.82 kV, β = 1.50

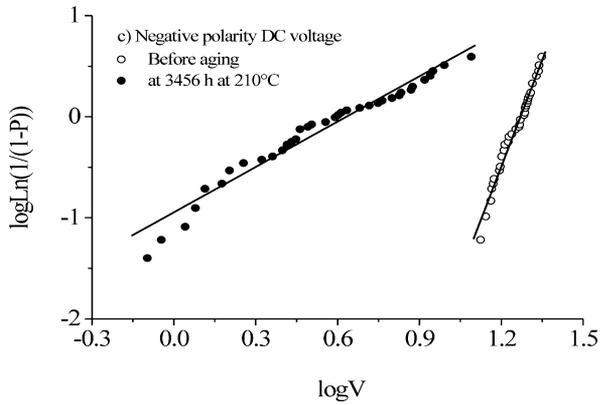
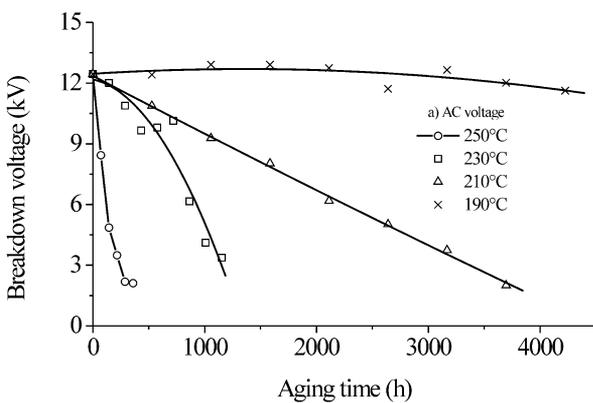


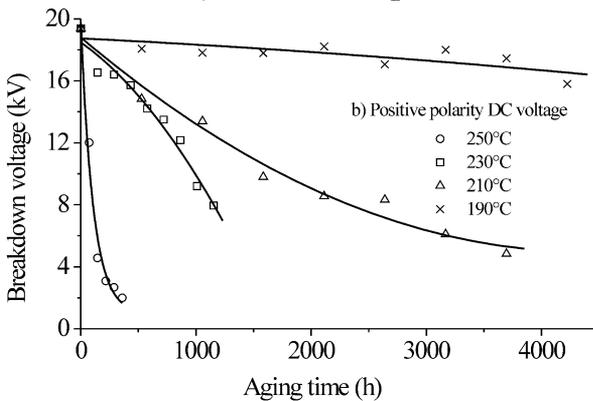
Figure 1c. Weibull graph of negative polarity DC breakdown voltage

Before aging: $V_0 = 18.66$ kV, $\beta = 7.64$

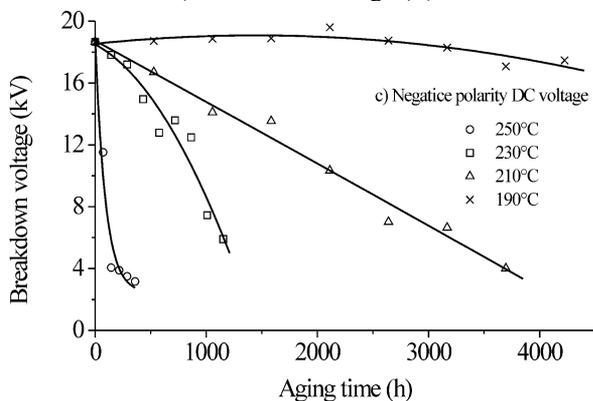
After 3456 h at 210°C: $V_0 = 4.31$ kV, $\beta = 1.50$



a) Under AC voltage



b) Under DC voltage (+)



c) Under DC voltage (-)

Figure 2. Evolution of breakdown voltage against aging

4.2 Dependence of breakdown voltage on aging

Figure 2 shows nominal breakdown voltage (63.2%) against aging. The evolution can be summarized as follows:

4.2.1 Under AC voltage

- At 190°C, the breakdown voltage is practically unvarying with aging time. V_0 decreases slightly from 12.50 kV to 11.63 kV after 4224 h. The maximum variation is 6.58% and seems insignificant.
- At 210°C, V_0 drops from 12.45 kV to 2.15 kV after 3694 h. The maximum variation is 82.73%.
- At 230°C, V_0 decreases rapidly from 12.45 kV to 3.38 kV for 1124 h. The maximum decrease is 72.85%.
- At 250°C, the breakdown voltage falls from 12.45 kV to 2.07 kV after 362 h. The maximum decrease is 83.37%.

4.2.2 Under positive polarity DC voltage (+)

- At 190°C, V_0 slopes down slowly from 18.72 kV to 16.53 kV for 4224 h. The maximum changing is 11.69%.
- At 210°C, V_0 falls from 18.72 kV to 5.33 kV after 3699 h. The maximum changing is 71.52%.
- At 230°C, V_0 diminishes from 18.72 kV to 7.98 kV for 1158 h. The maximum changing is 57.37%.
- At 250°C, V_0 drops from 18.72 kV to 1.64 kV after 363 h. The maximum changing is 91.23%.

4.2.3 Negative polarity DC voltage (-)

- At 190°C, V_0 shortens slowly from 18.51 kV to 17.10 kV for 4224 h. The maximum variation is 7.61%.
- At 210°C, breakdown voltage drops from 18.51 kV to 3.96 kV after 3688 h. The maximum variation is 78.60%.
- At 230°C, V_0 starting at 18.51 kV, goes down to 5.97 kV after 1155 h of aging. The maximum variation is 67.74%.
- At 250°C, V_0 decreases sharply from 18.51 kV to 2.73 kV after 362 h. The maximum changing is 82.25% which can be explained by the fact that the anti-degradants added in the blending were practically consumed.

4.3 Thermogravimetric analysis

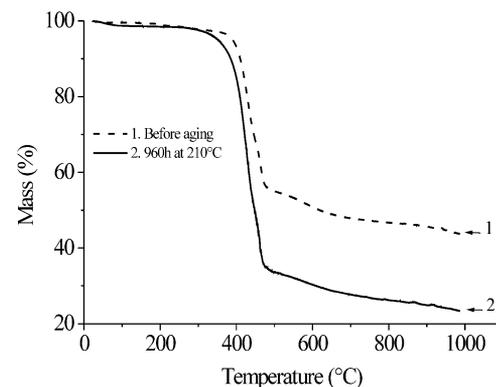


Figure 3a. TGA thermograms before aging and after 960 h at 210°C

The variation of polyesterimide mass as a function of temperature is studied. The obtained TGA thermograms, as shown in Figure 3a and 3b, have the same shape. In Figure 3b, the curves are almost the same. For all the thermograms, a small mass loss can be observed between 100°C and 275°C. This process is due to the evaporation of water and solvents.

As one can see, there is one stage of decomposition process which can be described as follows:

- Before aging, the mass loss starts at around 395°C, accelerates and reaches 52.2% at a temperature of 477°C. Then it slows down at around 600°C. The remaining residue is of 43.7%.
- For the samples aged during 960 h at 210°C, the mass loss begins at a temperature about 386°C. Beyond the onset temperature, the mass falls to 30.7% corresponding to a temperature around 475°C. At this temperature, the mass loss decelerates and it assumes a residue of 23.4%.
- After 1920 h at 210°C, the mass loss begins at around 388°C, speeds up until 34.9% for a temperature about 466°C. Afterwards the mass loss decreases slowly and it remains a residue of 27.5%.
- For the specimens aged until 3456 h at 210°C, the mass loss starts at around 376°C and decreases rapidly to 37.3% for a temperature about 462°C. Then the curve indicates a slow-down process leading to a residue of 25.7%.

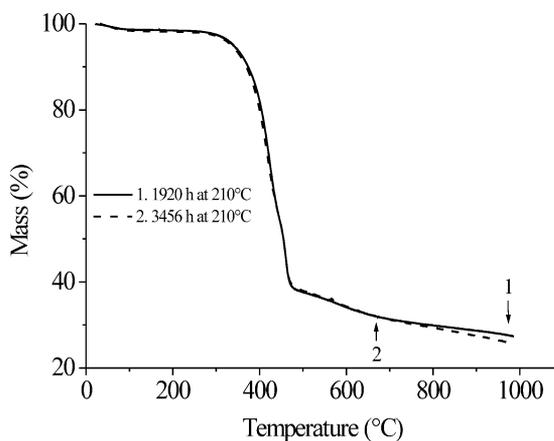


Figure 3b. TGA thermograms after 960 h and 3456 h at 210°C

4.4 Differential scanning calorimetry

Figure 4 shows DSC thermograms before and after aging. The curves show the appearance of a glass transition phase which is delimited by $T_{g_{min}}$ and $T_{g_{max}}$. The glass transition temperature (T_g) is taken as the middle point of the transition. The results are exposed in Table 1.

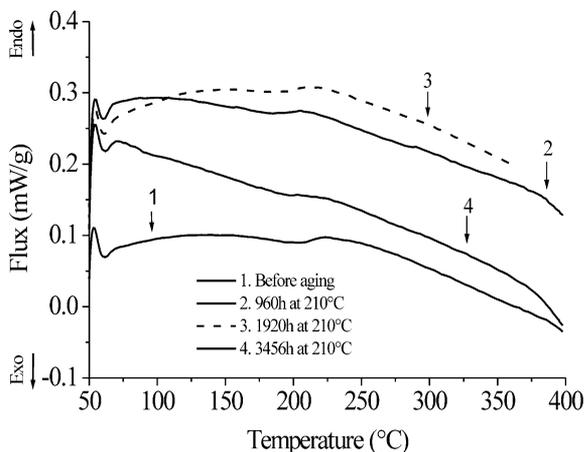


Figure 4. DSC thermograms before and after aging

Table 1. Results of DSC measurements

Aging time (h)	$T_{g_{min}}$ (°C)	$T_{g_{max}}$ (°C)	T_g (°C)
0	205	224	215
960	182	209	196
1920	194	214	204
3456	191	217	203

4.5 Discussion

1. The TGA thermograms show that the onset temperature of mass loss and the residue are larger in the case of non – aged samples. The values of glass transition temperature, determined by DSC, are in agreement with those reported by Guan et al. [15] that is usually located in the interval 200-250°C. The glass transition temperature has a tendency to decrease versus aging time, thus resulting in a plasticization of the material. The results of TGA and DSC highlight the degradation of the polymer.
2. During the aging, copper dissolves at the interface of polyesterimide – copper [6]. The oxygen can diffuse into the material and attacks copper, resulting in the formation of copper oxide. The decomposition is induced by a scission reaction of imide - bond and ester - bond. This process is accelerated in the presence of copper wire activating as a catalyst [6]. Burrell and Keane [16] reported that copper was found in the polyesterimide films after aging process at 230°C. The copper oxide grows into the dielectric material and reduces its thickness.
3. In solid insulating materials, internal defects as voids, metallic inclusions, cracks, interfacial defects can be formed during the manufacturing process and after aging. Partial discharges take place when the electrical field exceeds the breakdown strength of the gas (air or others) contained in the cavities, thus resulting in the degradation of the dielectric material. The action of these discharges induces an initiation of electrical tree, whose propagation leads to failure. During the breakdown tests, discharges take place on the surface of the samples. They heat the solid dielectric and accelerate the degradation.
4. For all temperatures, the breakdown voltage decreases against aging time. The more the temperature is high, the fast the material degradation occurs. The decrease is allotted to a shortening in viscosity resulting to a weakening of the molecular bonds. Thereby, the free volume raises and leads to an increase in mean free path of charge carriers whose mobility rises.
5. After 3456 h at 210°C, the shape parameter is smaller than that before aging. It may be due by the fact that size and number in defects increase. This phenomenon was indicated by Coppard et al. [17]. Katsuta et al. [18] found that breakdown voltage of crosslinked polyethylene and shape parameter depend on the kind and the size of defects.
6. The DC breakdown voltage is greater than that AC breakdown voltage. It is allotted, in part, to the dissipated energy difference under the two types of electrical field and, in the second place, due to the fatigue induced by the AC voltage. This phenomenon has been pointed out by Crine [19]. The dielectric breakdown is related to the amount of space charge contained in the material. Indeed, in this study the electrical field applied to the specimens is about 1MV/cm and space charge can be built at the polymer-copper interface and affects breakdown dielectric, as indicated by Mammeri et al [20] and Malec [21], It is reported that space charge content in samples aged under

AC field is always significantly shorter than that under DC field [19]. DC breakdown voltage belongs on the polarity. This phenomenon is allotted to the different amounts of the space charge accumulated under the two polarities. It was indicated effect of the form of applied voltage on dielectric breakdown [22-25]. Gockenbach and Schiller [22] found that the highest breakdown voltage of XLPE was measured at DC voltage with negative polarity and the lowest at AC voltage. In previous works, we pointed out that breakdown voltage of polyesterimide, polyamide imide and polyvinyl chloride depends on the shape of applied electrical field [23, 24]. Idriessu et al. [25] reported that under DC stress, the initiation and growth of electrical trees are dependent on the polarity.

5. CONCLUSIONS

This investigation exhibits that breakdown voltage of polyesterimide enamelled copper wire reduces with aging time. It is ascribed to the increase in mean free path of charge carriers resulting in the raise in free volume. It is pointed that the shape parameter of Weibull plots after 3456 h at 210°C is lower than that before aging. It is ascribed to the increase in size and number in defects within the material. The values of DC breakdown voltage are bigger than those under AC electrical field. It is assigned to the dissipated energy difference under the two types of electrical field strength; and the fatigue causes by AC voltage. The results show that the DC breakdown voltage is linked to the polarity of applied electrical field. It is due to the difference amounts of space charge accumulated in insulation under the two polarities. The glass transition temperature decreases versus aging time. It is attributed to the plasticization of the polymer. The TGA thermograms indicate that the onset temperature of mass loss and the remaining residue are bigger before aging. The degradation occurs at the interface of polymer-copper by scission reaction of imide –bond and ester-bond. The degradation is hastened by the dissolution of copper.

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