Investigation of the long term degradation of cellulosic insulating materials in high voltage power transformer

NIHAT PAMUK*
Turkish Electricity Transmission Company / 54100 - Sakarya, Turkey

Power transformer is one of the most expensive and strategically significant components of any power system, so that they are crucial parts of high voltage energy generation and transmission systems. Therefore their function is essential to power system reliability. This paper presents the life and long term degradation of oil impregnated cellulosic insulating materials used in power transformers. The purpose of this paper, changes of mechanical and dielectric strength of cellulosic insulating materials was examined by accelerated aging experiment for one year. Then, cellulosic insulating materials used in large capacity power transformers which had been operated for several years and up to 20 years were investigated. One of the results derived from the above examination and investigation is such that the mechanical characteristics of cellulosic insulating materials have been degraded down to approximately 50 percent of the initial value through operating for 20 years whereas electrical characteristics are less degraded.

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1. Introduction

The effective operation of high voltage power system equipment is very dependent on the right choice of insulating materials and maintaining them in good condition during their life. This involves knowledge of the types of conventional and modern materials available and how they would be anticipated to behave in the appropriate operating environment, particularly over long periods.

Electrical aging is always a significant problem of concern to industry. Electrical aging is a step by step degradation action leading to catastrophic breakdown of the material. Apparently, the lifetime of an electrically stresses material depends upon the magnitude of the electric stress practiced to the material and the length of the time it has been exposed to such a stress. This mentions that the lifetime of a material depends chiefly upon the electrical contacts, which control courier injection, and the kind and concentration of courier traps, which control the degradation action [1].

The main solid insulating materials used in an oil filled power transformer are cellulose materials such as pressboard and paper. These solid insulating materials must have adequate dielectric and mechanical strength. It is essential for the reliability of the power transformer to understand how the dielectric and mechanical strength of those materials changes during an operating time [2].

Until the present, several reports have been indicated about the degradation of the tensile strength and polymerization of cellulose materials [3, 4, 5]. However, these reports do not exhibit sufficient identification regarding the degradation of power transformers. An investigation has been produced which is appointed a construction ratio of copper, steel and insulator almost similar to that in the power transformer.

This paper was exposed to accelerated aging experiment at temperatures of 100 to 180 ^{o}C for one month to one year to inspect the changes of cellulosic insulating material’s characteristics. Creped papers and insulating kraft used in power transformers were sampled at the times of overhauls and interior examination of large capacity power transformers indeed acted to investigate variations in their characteristics. Lastly, it discusses the reasonableness of accelerated aging experiment and the long term reliability of power transformer by comparing results of the above experiment and investigation of power transformer with each other.

2. Electrical aging

Most electrical failures are induced by electrical aging, partial discharge or breakdown from insulating materials in electrical or electronic engineering systems. The failure of power transformers and the failure of electronic elements are involving thin insulating layers, such as silicon dioxide or silicon nitride thin layers in the industry.

2.1 Measurements of electrical aging

The limit of electrical aging of an electrically stressed insulating material can be regarded the degree of structural degradation [6], which can be measured as the rate of the change in the features of the material that is to say, the rate of the strengthen in the concentration of the stress created new traps. Hence, the lifetime depends upon the electrically stressing condition. The lifetime can be chastely described as the time involved for the concentration of the stress created new traps to reach an explicit critical value. Electron paramagnetic resonance spectroscopy can be used to designate free radicals and predict their concentration [7]. Some empirical results indicate that the free radicals generated in polypropylene. The energy improved by virtue of electron trapping or reunification events is disheveled in breaking the bonds of macromolecules to generate free radicals. The ends of the broken bonds with unpaired electrons will move as receptor like electron traps.

The trapped carriers will be thermally removed to the conduction band and then discharged at both electrodes. During a period of short-circuiting, the concentration of trapped electrons is higher near the electron injecting contact and reduces with x toward the non injecting contact, and at point x_1 the interior field F_{in} = 0 [8], as shown in Fig. 1.

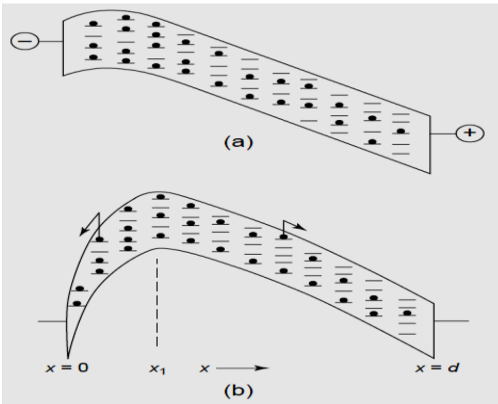

Fig. 1. Schematic energy band diagrams for insulating materials; (a) at the period of being electrically stress and (b) during discharging.

The field distribution at $x < x_1$ and $x > x_1$ can be explained as

$$F = -(\frac{q}{\varepsilon})\int_{x_1}^{x} n_t(\mathrm{x})\,\mathrm{dx} \qquad (1)$$

where $n_t(x)$ is the trapped electron concentration distribution function. Since the two short-circuiting electrodes are at the identical potential, the position of x_1 can be designated from the following equation;

$$V = -\int_0^d F\,\mathrm{dx} = (\frac{q}{\varepsilon})\int_0^d \int_{x_1}^{x} n_t(\mathrm{x}^{\mathrm{I}})\,\mathrm{dx}^{\mathrm{I}}\,dx = 0 \qquad (2)$$

The interior field F_i is controlled by $n_t\ (x)$. The larger the value of $n_t\ (x)$ near the injecting contact, the closer point x_1 is to the injecting contact. So the higher the field is toward the injecting contact as shown in figure 1(b). It is probable that x_1 is very close to the injecting contact. According as the concentration of the accumulated trapped electrons $n_t\ (x)$, it is feasible that after prolonged electrical stressing, $n_t\ (x)$ may get such a level that F_i becomes high enough to cause an interior discharge, leading to ultimate, subversive breakdown of the specimen when short-circuiting the electrodes. Assuming that the probability for the conception of a new trap under an average field F is γ, then the rate of the new trap conception can be written as

$$\frac{dN_t^{'}}{dt} = \frac{\gamma J(\mathrm{t})}{q} \qquad (3)$$

where N_t^1 is the newly created trap density and $J(t)$ is the injected current concentration [9]. The probability γ can be considered a field activated process, expressed as

$$\gamma = \gamma_0 \exp(\mathrm{BF}) \qquad (4)$$

$$J = J_0(1 + Kt^{-m}), \mathrm{t} > 0, 0 < m < 1 \qquad (5)$$

where γ_0 and B are constants related to the chemical structure of the material [10-11]. J is proportional to t^{-m}, with m close to unity. So, J can be reasonably expressed as equation 5. In equation 5, K and m are constants depending upon the material structure and the potential barrier profile of the injecting contact, and after the current decay transient period, J_o is the quasi-steady state current, which is field dependent. Replacing equations 4 and 5 into equation 3 and solving it with the limit condition $N_t^1 = 0$ at $t = 0$,

$$N_t^{'} = \frac{\gamma_0 J_0\,\mathrm{t}}{q}(1 + \frac{K}{1+m}\,\mathrm{t}^{-m})\exp(\mathrm{BF}) \qquad (6)$$

For extensive electric stressing, the term $Kt^{-m}/(1-m)$ becomes much smaller than 1. Afterwards, equation 6 can be simplified to;

$$N_t^{'} = \frac{\gamma_0 J_0\,\mathrm{t}}{q}\exp(\mathrm{BF}) \qquad (7)$$

Supposing that J_o is commensurate to F and that catastrophic breakdown take places when the density of the field created new traps reaches an apparent critical value $N'_{t(crit)}$, then the lifetime t of an insulating material subjected to a stressing field F can be estimated by

$$N_{t(\mathrm{crit})}^{'} = AtF\exp(\mathrm{BF}) \qquad (8)$$

where A is a constant depending upon the material structure and the potential barrier profile of the injecting contact [12].Therefore, for a fixed applied stressing field F, the lifetime of the polymer is t, and for a fixed stressing time t, an average stressing field F is required to create $N^{'}_{t(crit)}$, that is to cause catastrophic breakdown.

2.2 Aging of cellulose

Cellulosic materials have been used in the insulation system of power transformers and power cables for a long time [13, 14]. Cellulosic insulation materials have been proven to desirable chemical and physical properties for use as electrical insulators, but they degrade as the materials age. So, the degradation of the cellulosic materials is a crucial factor in determining the life of power transformers and power cables. In all applications, methods of characterizing cellulose degradation and kinetics of cellulose degradation evolution are significant, because they not only rule the long term performance of the paper products but also ultimately decide the beneficial power cables and power transformers.

The characterization of the degradation includes choosing a suitable variable to describe the defects of the cellulose at the molecular level, and to discover how these defects affect the macroscopic behaviors of the cellulose [15, 16]. It is well noticed today that all photolytic, hydrolytic, thermal, photochemical and enzymatic degradation of cellulose are actually because of the scission of polymeric chains (a number of the β glycoside bonds being broken). A simple molecular structure of cellulose is shown in Fig. 2.

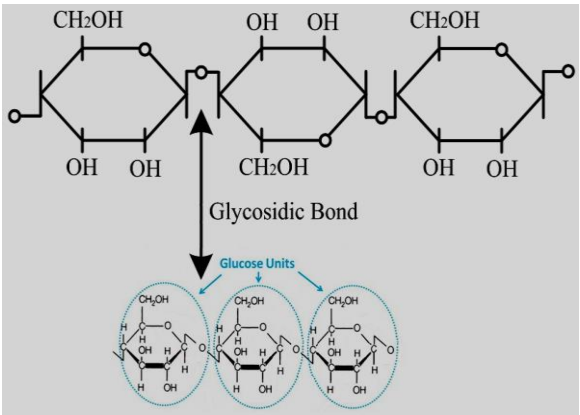

Fig. 2. Structural formula of cellulose.

Cellulose is a linear polymer of glucose; consisting D-anhydroglucopyranose units joined together by glycoside bonds. A single cellulose fiber is formed from a number of these chains held together by hydrogen bonds [17]. Degree of Polymerization (DP) is the measurement of average number of glucose units per molecular bond. Paper insulation with greater than 1000 DP, indicates high tensile and dielectric properties, whereas DP value less than 300 demonstrates a paper with poor dielectric and mechanical properties [18]. Existence of oxygen and water in the insulation system accelerates the aging phenomenon. Oxidation, Pyrolysis and Hydrolysis are the three mechanisms, moving at the same time. The aging mechanism affects the mechanical and electrical properties of the dielectrics [19].

3. Experimental Details and Results

This section presents some typical experimental details and results showing the degree of electrical aging for broadly used insulating polymers, such as polypropylene and polyethylene, and correlates. In polymers, structural degradation can be diagnosed by measuring the density of free radicals formed in the polymer owing to continuous electrical stressing. The experimental model was manufactured which consist of an aluminum pipe having insulating paper wound thereon. The characteristics of the insulating paper are shown in Table 1.

Table 1. Characteristics of insulating paper.

Characterization of insulation paper	Values
Tensile Strength Lengthwise	13.2 kg/mm^2
Tensile Strength Crosswise	2.8 kg/mm^2
Elongation Lengthwise	1.8 %
Elongation Crosswise	8.5 %
Thickness	0.074 mm
Impermeability	775 sec/100 ml
Water Content	8.5 %
Density	0.84 g/cm^3
Acid Value	0.06 mg.KOH/g
Dielectric Breakdown Voltage	10.8 kV/mm

The experimental model had been dried for 24 hours at a temperature of 110 ^{o}C in a temperature controlled bath; it was put into a stainless steel vessel together with copper plates and core steels. The component ratio of the materials in the vessel is shown in Table 2.

Table 2. Component ratio of materials.

Components	Weights
Core Steel	1165 gr
Insulating Oil	3060 gr
Insulating Paper	552 gr
Aluminum Pipe	645 gr
Copper Plate	807 gr

The component ratio of the material is almost the same as that in a typical large capacity high voltage oil filled power transformer, and then the vessel was dried for 4 hours at a temperature of 110 ^{o}C and a pressure of less than 0.5 Torr, was deprived of air with temperature diminishing, supplied with oil, injected with one atmospheric pressure of nitrogen, and sealed. The characteristics of the insulating oil used are shown in Table 3.

Table 3. Characteristics of insulating oil.

Characterization of insulation oil	Values
Resistivity (25 °C)	1.0 x 10^{17} Ωcm
Resistivity (80 °C)	1.0 x 10^{16} Ωcm
Dielectric Loss Tangent (25 °C)	< 0.001 %
Dielectric Loss Tangent (80 °C)	< 0.001 %
Kinematic Viscosity (40 °C)	8.3 cSt
Kinematic Viscosity (75 °C)	3.4 cSt
Flash Point (°C)	136
Pour Point (°C)	-32.5
Acid Value	0.002 mg.KOH/g
Oxidation Acid Value	0.20 mg.KOH/g
Oxidation Sludge	0.10 %
Specific Gravity (15/4 °C)	0.878
Dielectric Breakdown Voltage	>70 kV/2.5mm

The experimental model in a vessel was subjected to accelerated aging experiment in a temperature controlled bath at temperatures of 110 to 180 °C for one month to one year. After the accelerated aging experiment, the model was taken out of the stainless steel vessel to measure its electrical and mechanical characteristics.

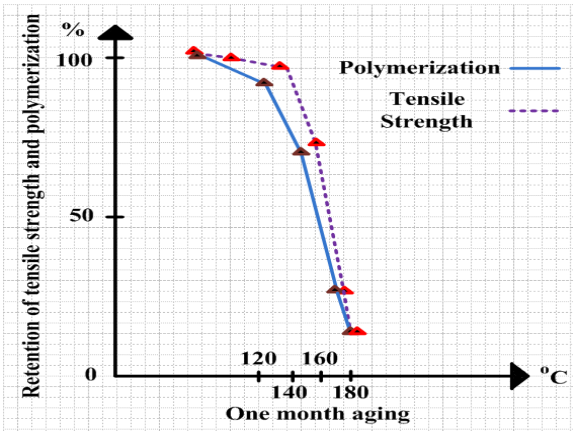

Fig. 3. Mechanical property.

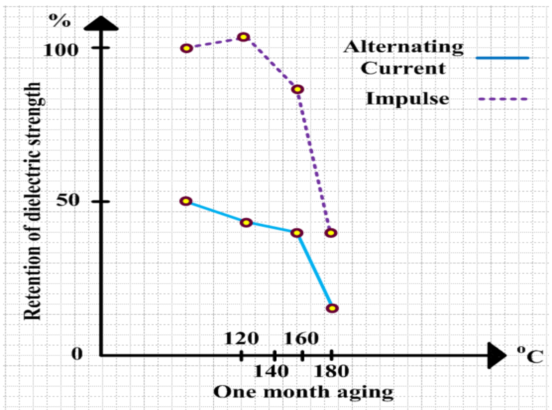

Fig. 4. Dielectric strength.

Fig. 3, Fig. 4 and Fig. 5 illustrate the characteristics of the model measured after one month aging. Fig. 3 illustrates the heating temperatures on the abscissa and the retention of tensile strength and polymerization on the ordinate. Fig. 4 illustrates alternating current breakdown voltage and impulse breakdown voltage (in percent age) compared with the initial value of impulse breakdown voltage (100 percent). Fig. 5 illustrates the water content in oil and paper (in ppm).

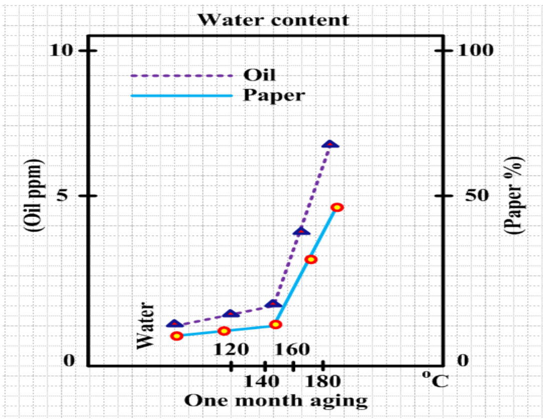

Fig. 5. Water content in oil and paper.

In the case of one month aging, important differences were found between characteristics at less than 140 °C and those at 180 °C; the tensile strength and polymerization of insulating paper are considerably degraded at a heating temperature of 180 °C. The dielectric strength for alternating current breakdown voltage and impulse breakdown voltage was also importantly lowered at a heating temperature of 180 °C probably because of much water content produced in oil and paper as shown in fig. 4 and Fig. 5. The breakdown voltage measured for the model after it had been aged for one month at a temperature of 180 °C and deprived of water content illustrates little deterioration. Therefore, the deterioration of the breakdown voltage at a temperature of 180 °C would be owing to water content increased by degradation.

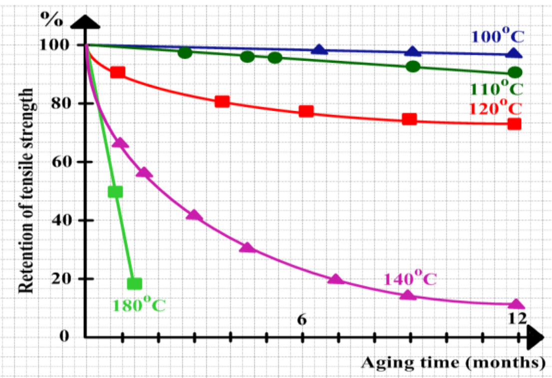

Fig. 6. Tensile strength of aged insulating paper.

Fig. 6 and Fig. 7 illustrate variations of the tensile strength and polymerization of the model measured after it had been aged for one month to one year. These figures reveal that the model was degraded importantly at more than 140 °C rather than at less than 120 °C and that the deterioration of polymerization preceded that of tensile strength.

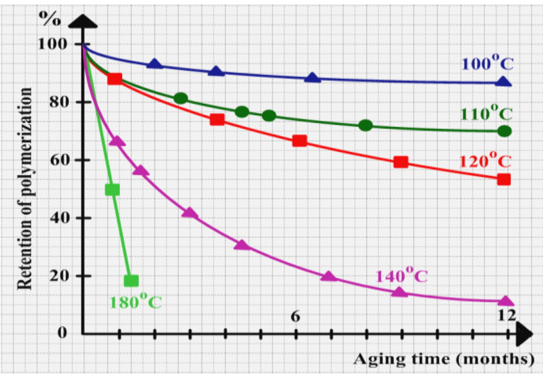

Fig. 7. Polymerization of aged insulating paper.

4. Investigation of power ageing transformers insulating materials

Fig. 8, Fig. 9 and Fig. 10 illustrate results at investigating the mechanical and dielectric strength of insulating paper sampled from power transformers at times of overhaul and internal inspection.

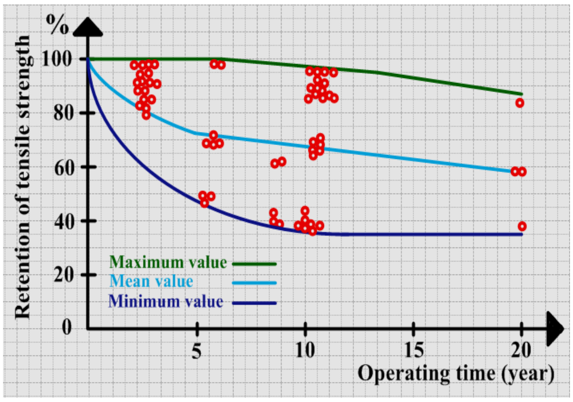

Fig. 8. Degradation of tensile strength.

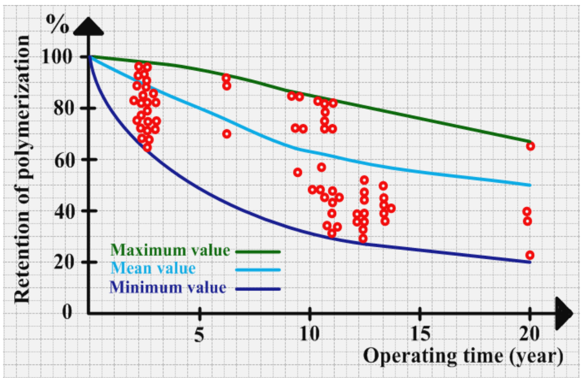

Fig. 9. Degradation of polymerization.

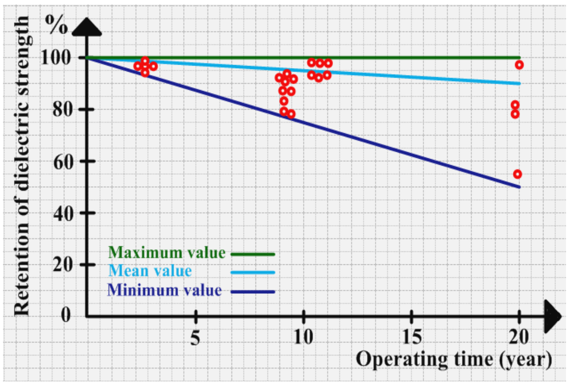

Fig. 10. Degradation of dielectric strength.

In these figures, the characteristics of new sample of the insulating paper used in the power transformers were taken as 100%. Maximum envelopes, mean lines and minimum envelopes are shown in these figures. The results derived from power transformers exhibits considerable deviations; for example, the tensile strength of insulating paper of a power transformer operated for about 10 years ranged approximately from 40 through 100 percent of the initial value. This would be because the operating conditions and treatment conditions during assembly differed among the power transformers and also because the temperature duties were different depending upon the sampling places. Simple prediction of the characteristics without allowing for any thrives of materials used for 20 years in power transformers leads to a conclusion that the mean value of mechanical strength including tensile strength and polymerization is lowered by approximately 50 percent for 20 years; but, the dielectric strength is lowered only by approximately 15 percent in 20 years. Fig. 11 illustrates the relation between tensile strength and polymerization.

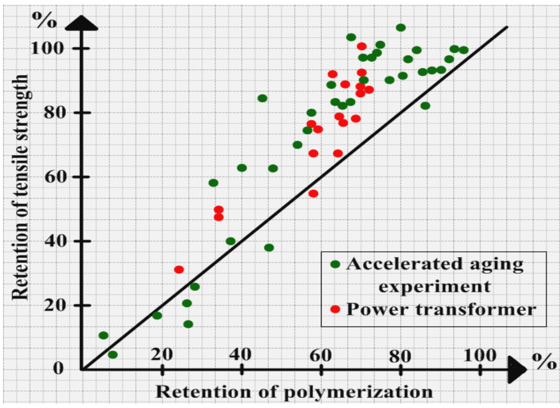

Fig. 11. Relation between tensile strength and polymerization.

The data determined from accelerated aging experiment and the data determined from power transformers, both of which exhibit low deterioration of tensile strength compared with polymerization in the initial degradation step, indicate a similar tendency. This permits simulating the deterioration of the power transformer by accelerated aging experiment. Fig. 12 and Fig. 13 illustrate variations of tensile strength and polymerization identified against aging periods (operating years) by using aging temperature as the parameter.

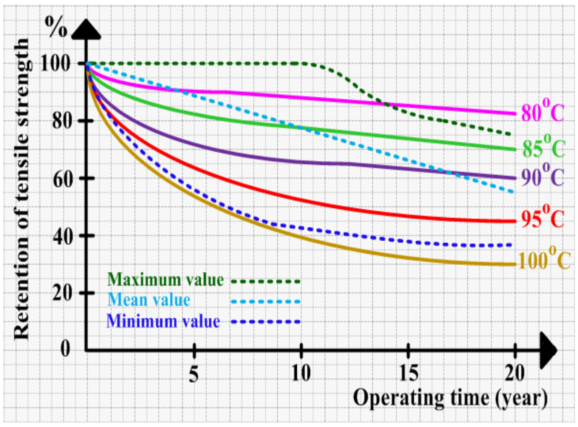

Fig. 12. Degradation of tensile strength and its temperature.

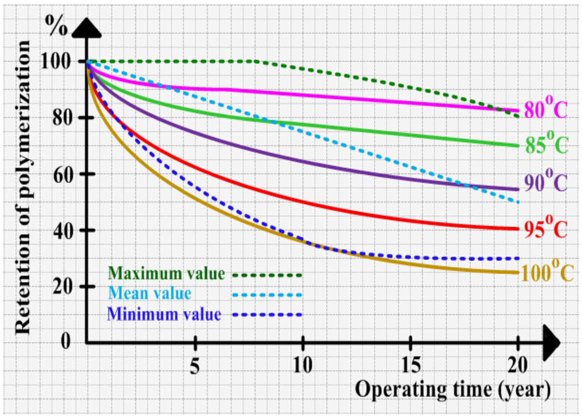

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Fig. 13. Degradation of polymerization and its temperature

A comparison of these variations with the data from the power transformer reveals that the deterioration characteristics at a temperature of 100 °C approximate the minimum envelope and those at a temperature of 90 °C approximate the mean value line of the power transformer; material degradation characteristics of the power transformer coincide almost with long term degradation characteristics at a temperature of 90 °C which is somewhat higher than the actual mean operating temperature. This is because no improvements in the material itself, or in material treatment technology, or in oil conservation technology have been allowed for; the thermal deterioration of recent power transformer insulating materials would be smaller than those shown in Fig. 8, Fig. 9 and Fig. 10.

5. Conclusion

The results of accelerated aging experiment conducted for one year have been compared with the results derived from power transformers, and the following points were clarified:

1) The degradation of insulating materials in an operating power transformer may be simulated by the above-mentioned accelerated aging experiment providing the same material component ratio as the power transformer.

2) In power transformer, both tensile strength and polymerization are lowered down to approximately 50 percent of the initial value owing to operation for 20 years, whereas the dielectric strength is lowered only by about 15 percent.

3) The average deterioration characteristics of the power transformer coincide almost with deterioration characteristics at a temperature of 90 °C, and the minimum envelope corresponds almost to deterioration characteristics at a temperature of 100 °C.

It will be helpful to verification of the long term reliability of power transformer insulation that the degradation characteristics of the insulating materials used in the oil filled power transformer were clarified and the correlation of experimental results with data for power transformer were identified.

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*Corresponding author: nihatpamuk@gmail.com