Thermal Lifetime of Transformer Electroinsulating Oils

ELENA HELEREA¹, ADRIAN MUNTEANU¹
Department of Electrical Engineering
University Transilvania of Brasov
29, Bd. Eroilor, Brasov, 500025
ROMANIA
helerea@unitbv.ro, adrian.munteanu@unitbv.ro http://www.unitbv.ro

Abstract: The paper deals with the evaluating the thermal lifetime of the electro insulating transformer oil as part of the prognosis of the remaining lifetime of the transformer as a whole. The thermal-oxidative ageing accelerated tests have been carried out for the oil samples TR 25A at the temperatures of 100 - 130ºC, with the control of the oxygen content, the temperature and the catalysts. The measured parameters have been the dielectric losses factor, the index of neutralization at the temperature of 20ºC, and the interfacial tension against the water at the temperature of 20ºC. The data proceeding allow the obtaining the model of thermal-oxidative degradation process, described by a combined function in dependence on temperature and time. The proposed combined function expression was experimental validated. Based on this relation, a procedure for prognosis the lifetime of the oil was established.

Key Words: thermal lifetime, oils, transformer, prognosis, interfacial tension.

1 Introduction

In recent years the interest in the theoretical study of Power transformers are main equipment of power system, and their good operation is essential for safety and reliability of all chain of delivery electrical energy. Nearly all distribution transformers are filled with oils, which has the functions both, as electrical insulation, and as a cooling system. To assure these functions, the specific requirements are imposed for electro insulation oils [1].

Electrical insulation system, specially transformer oil id subjected to several types of stresses: electrical, thermal, environmental, and mechanical stresses. Thermal stress is important stress factor. Typical operating temperatures for power transformers are between 60 ºC to 100 ºC. At these values of temperature, the transformer insulation system – paper, pressboard, and mineral oil - undergo slowly ageing with continuous loss on mechanical, electrical and chemical properties. The specific form of ageing depends on the material type, and is due to chemical (oxidation and hydrolysis) and physical degradation. The ageing processes in oils are intimately connected with the amplitude and duration of the thermal stresses, which change their physic and chemical properties. Therefore, carefully designed and controlled laboratory scale tests should be designed and performed, to asses the ageing processes. The aim of these tests is to create the conditions favorable for rapid deterioration of oil, and to observe and monitor all the properties during ageing process. The acceleration of the ageing process saves time, specially, when the time to failure of insulation follows an inverse power law of electric stress, and an Arrhenius rate process of thermal stress. Many roles have been established for an optimum design of accelerated tests. The more important observed parameters are: moisture content, capacitance and dissipation factor, dielectric breakdown strength, micro-particle count, dissolved gases, and furfurals, as final products of thermal degradation of cellulose insulation [2].

In recent years, many researches have been developed regarding the non-destructive ageing tests and new models have been developed for predicting the remaining life of oils, insulation system, even for hole transformer [3].

Indicators of ageing process such as yellowing, oxidation, increased acidity and water content have been also reported [4]. Interfacial tension is a parameter used for the qualitative characterization of oils, the value of 0.040 N/m indicates the absence of undesirable polar contaminants. Proposed limit of acceptance is of 0.045 N/m [5]. Neutralization number (acidity) ia a measure of the trace amount of acidic or alkaline contaminations in the oil. A long life expectancy of oils in transformers is obtained if the neutralization number is lower then 0.01 mg KOH/g. Proposed limit for acceptance is of 0.025 mg KOH/g [5].
Modern techniques of diagnosis for assessing the insulation system condition in aged transformers are also developed. Among these techniques, polarization/depolarization current measurement, return voltage and frequency dielectric spectroscopy are proposed. In frequency domain dissipation factor or $\tan \delta$ is measured as the frequency dependent ratio of imaginary and real parts of the complex permittivity. The independence of the geometry makes dissipation factor one of the important parameters to study ageing, when the geometry of test varies for is not known [6].

2 Ageing curves and endurance curves

The simplifying assumptions used in mathematical modeling are the following:
The diminution in feasibility of the technical systems may be explained, in the last analysis, through the modification of the system functions, the cause being the wear and tear and ageing of the system components, respectively of the component materials.
The ageing of a material is a complex process, in which the material properties modify in time, following the action of intrinsic and/or extrinsic factors.
There are at present manifold physical-chemical theories upon ageing, which justify the degradation processes, but which are difficult to use in predicting the lifetime of the material, respectively of the components, technical systems.
As an alternative, the ageing phenomenological theories mainly consider the ageing effects, experimentally emphasized.
This way, for the material-strain conditions assembly, the behaviour function may be considered.

$$f(P, S, t) = 0$$

where $P$ value represents a material macroscopic property, $S$ is the strain intensity, $t$ the time variable.
Geometrically, the equation (1) represents curvilinear surfaces which, through intersections with planes of the type $S=\text{const.}$, respectively, $P=\text{const.}$, generate curves, called:
- ageing or degradation curves:
  $$f(P, t)_{S=\text{const.}} = 0$$
  (2)
- durability or endurance curves:
  $$f(S, t)_{P=\text{const.}} = 0$$
  (3)

The lifetime $L$ of a material is defined as that interval of time in which a physical quantity of material $P$, named degradation indicator varies under the action of the $S$ intensity strain, starting from a $P_0$ initial value, corresponding to the non-degraded state, until a $P_{\text{cr}}$ limit value, named end of life criterion, for which the material no longer satisfies the functional requirements.
The chosen value in order to define the limit value is set through convention. For instance, in many cases, the limit (critical) value is considered half the initial value of the dielectric rigidity – for which value the material is deemed to have lost its quality of electric insulator, under conditions of normal utilization.
The lifetime curve is the durability curve for the limit case:

$$f(S, L) = 0_{P=P_{\text{cr}}}$$

(4)

This way, in order to deduce the lifetime curve, the behaviour function must be known (1). Usually, solely the ageing curves can be experimentally obtained without difficulty. It is necessary to settle procedures for determining the lifetime curve, knowing the ageing curves.
A first problem consists in settling the analytical form of the ageing curves, starting from the experimental data.
In line with the experimental data, Dakin and Mamlow propose, for the ageing curves, expressions such as:

$$\frac{dP}{dt} = -K \cdot P^\alpha \bigg|_{S=\text{const.}}$$

(5)

where $K$ is a parameter depending on the $S$ strain, and $\alpha$ is a parameter having the physical sense of ageing reaction order.
The equation proposed by Simoni, which should describe the different forms of variation in time of the ageing curves is of the form:

$$\frac{dP}{dt} = -K(S) \cdot P^\alpha \bigg|_{S=\text{const.}}$$

(6)

where $\alpha \in R$ and $K(S) = \text{const.}$ for $S=\text{const.}$ and the reported value of the $P(t)$ property is a time variable monotonic function, starting from the initial value of the $P_0$ property:

$$p(t) = \frac{P(t)}{P_0} \in [1, 0]$$

(7)

Through integrating the equation (6) the expression of the ageing curves ensues, of the form:

$$P^{1-\alpha} = 1 - (1-\alpha) \cdot K(S) \cdot t$$

(8)
for $\alpha \neq 1$ and
\[ \ln p = -K(S) \cdot t \] (9)

for $\alpha = 1$.

Through extending the values of the parameter $\alpha (\alpha \in R)$, all types of ageing mechanisms may be described, the relations (8) and (9) being general relations of the ageing curves. Imposing the condition of reaching the end of life criterion ($p = p_{cr}$) the expression of the lifetime curve ensues, where:
\[ L = \frac{1 - p_{cr}^\alpha}{1 - \alpha} \cdot \frac{1}{K(S)} \] (10)

for $\alpha \neq 1$ and
\[ L = -\ln p_{cr} \cdot \frac{1}{K(S)} \] (11)

for $\alpha = 1$.

The lifetime duration is inversely proportional to the ageing speed $K(S)$.

The results of the ageing phenomenological theory are of a practical nature:
- Knowing the expression of the speed constant, with the relations (10) and (11), the lifetime may be predicted for a certain level of strain,
- Admitting the principle of duration – strain equivalence ($K(S) \cdot t = const.$), which considers that the same ageing level $p$ may be obtained for certain strain intensities $S_i$ at certain time intervals $t_i$. The accelerated, laboratory tests are thereby substantiated, in which the testing time is reduced through augmenting the strain.

3 Thermal Lifetime

In the case of the electro-insulating materials, the notion of thermal lifetime had been introduced by Steinmetz and Schüler, ever since 1913; however, a rigorous deduction of the thermal lifetime based on the experimental data was only made in 1930, by Montsinger, who proposed a dependent of the form:
\[ L = L_0 \cdot \exp\left[\frac{W}{RT}\right] \] (13)

Contributions are brought in 1948 by Dakin who, considering the theory of the chemical kinetics, obtains for the case of assimilating the reaction speed with the Arrhenius-type reaction the expression of the ageing curves:
\[ L(T) = \frac{1 - p_{cr}^\alpha}{(1 - \alpha) \cdot K(T)} \] (14)

for $\alpha \neq 1$ and
\[ L(T) = \ln\left(\frac{1}{p_{cr}}\right) \cdot \frac{1}{K(T)} \] (15)

for $\alpha = 1$.

The thermal life depends on the value of critical index $p_{cr}$ of the end of thermal life, imposed by the reliability requirements of the system in which the material is included. The parameters $\alpha$ and $K(T)$ are specific and characterize the process of time modification of the property charged as ageing criterion.

The slope of the kinetic plot (that is the reaction rate constant $K$) is related to temperature by the Arrhenius relationship:
\[ K(T) = K_0 \cdot \exp\left[\frac{W}{R(T + 273)}\right] \] (16)

where $\theta$ is temperature in °C, $R = 8.314$ J/moleK is gas constant, and $W$ is activation energy. Value $A$ depends on operation conditions [6]. Thus, the lifetime relationship become:
\[ L(T) = A \cdot \exp\left[\frac{B}{T}\right] \] (17)

According to Dakin, the ageing rate of the dominant ageing process depend on absolute temperature. Parameters $A$ and $B$ are determined experimentally [7].

4 A new approach of thermal life

The experimental data prove that for many material parameters the dependence upon temperature of the steady-state measured parameters (as: loss factor, neutralization index or interfacial tension) verify an equation of the type:
\[ p = a \cdot \exp(b \cdot \theta) \] (18)

where $p$ stands for the degradation criterion, and $\theta$
is temperature in °C. 
Also, the data obtained in thermal ageing at constant temperature indicate, for many ageing parameters, a dependance which is of the power type:

\[ p = m t^n + n t^{q} \]  \hspace{1cm} (19)

where \( t \) stands for the time of thermal ageing.

Taking into consideration that the three quantities which interfere with the processes of thermal degradation - the temperature \( \theta \), the time \( t \) and the degradation criterion \( p \) - stand for a surface in a three-dimension space, the modeling of the process of thermal-oxidative degradation to be carried out by a function like \([8], [9]\):

\[ p = f(\theta, t) = f_1(\theta) \cdot f_2(t), \]  \hspace{1cm} (20)

where the functions \( f_1(\theta) \) and \( f_2(\theta) \) are of the type:

\[ f_1(\theta) = a \exp(b \theta) \]  \hspace{1cm} (21)

\[ f_2(t) = m + n t^q. \]  \hspace{1cm} (22)

The function \( f_1(\theta) \) is a function of temperature whose expression is settled on the basis of the experimental determinations of the dependences \( p = f(\theta) \mid_{t=\text{const.}} \).

The function \( f_2(\theta) \) is a function of time whose expression is settled likewise on the basis of the attempts of accelerated ageing tests with the dependences \( p = f(\theta) \mid_{t=\text{const.}} \).

With the relations (19) and (20), the function \( f(\theta, t) \) becomes:

\[ p = f(\theta, t) = [a \exp(b \theta)] \cdot [m + n t^q] \]  \hspace{1cm} (23)

The thermal lifetime is obtained with relation (21) in which the value of the degradation criterion is considered equal to the value of the end life criterion \( p_{\text{cr}} \):

\[ L = \left[ \frac{p_{\text{cr}}}{a \exp(b \theta)} \cdot m \right]^{1 \frac{1}{q}} \]  \hspace{1cm} (24)

Relation (24) describes the cumulative process of degradation in time and with the temperature, in the case of thermal ageing tests for different degradation criteria taken into consideration.

5 Thermal accelerated ageing tests

5.1. Obtaining thermal ageing curves

The thermo-oxidative accelerated ageing tests on TR 25A type oil of 25 g samples have been carried out within the Laboratory of Physical-Chemical Tests of Electrica SA - Subsidiary of Braşov. The qualitative determinations were carried out in compliance with STAS 12044, CEI 666 and CEI 145.

The quantity of oxygen, the temperature and the catalysts have been strictly controlled. The aging parameters have been measured at the ageing intervals: 96, 120, 136, 164, 180, 216 hours. The following ageing parameters have been considered:
- loss factor (initial value at 90°C);
- neutralization index (initial value at the temperature of 20°C);
- interfacial tension (initial value at 20°C).

Working conditions for thermo-oxidative aging:
- oxygen flow: 1 l/h;
- working temperatures: 100°C, 110°C, 120°C, 130°C;
- catalyst: wire of electrolytic copper with a diameter of 1 mm with the length of 30.5 cm with whom there was carried out a spiral of 5 cm (9.7 cm²).

The ageing curves for measured parameters are shown in Fig.1, Fig.2, and Fig.3.

![Fig. 1. Ageing curves of loss factor for the TR 25A type oil samples aged at constant temperatures of 100 °C, 110 °C, 120 °C, 130 °C](image1)

![Fig. 2. Ageing curves of neutralization index, in mg/KOHg, for TR 25A type oil samples aged at constant temp.: 100 °C, 110 °C, 120 °C, 130 °C.](image2)
Some observations can be mentioned:
- In thermal ageing process of transformer oil the loss factor and the neutralization index rise with the temperature and in time, and the interfacial tension diminishes with the temperature and in time;
- As the temperature rises, the reaction speed of the oxidation increases too, and degradation products measured by the values of the de insoluble ones in n-heptanes and of the soluble products in chloroform are developed. At the temperature of 130ºC the quantities of the oxidation products significantly rise, and high values for the neutralization index appear. At this temperature, there also appears the danger of decomposition as regards the oxidation inhibitor;
- The oil ageing under the combined effect of the heat and of the oxygen leads to the apparition of the soluble oxidation products (acids) that alter the paper insulation and of the insoluble products (deposits) that alter the oil properties;
- The low values of the interfacial tension show advanced reactions of oxidation. This ageing parameter evolves very rapidly after the oil putting into service, without the other essential characteristics presenting any degradation. Thus, this property well reflects the general state of the liquid dielectric and should be a specific ageing indicator for insulation system and even for transformer. This opinion is justified, as the values of the interfacial tension are very much influenced by the presence of external substances dissolved in the oil: products of dissolution or degradation of the solid and liquid insulation.

5.1. Obtaining thermal lifetime curves
Following the experimental data processing, through a PLOT41 software there was noted that the equation (21) correctly describes the behavior of the oil, both with the temperature and in time, in the case that loss factor, neutralization index and interfacial voltage are considered as ageing criterions, the values calculated being close to the measured ones.

In obtaining the thermal lifetime curves, the following criteria of end of life are used:
- for loss factor, \( p_{cr} = 0.2 \);
- for neutralization index, \( p_{cr} = 0.2 \text{ mg/KOH/g} \);
- for the interfacial tension, \( p_{cr} = 20 \text{ dyne/cm} \).

With experimental data, using the criteria of end of life, the thermal lifetime curves are obtained and shown in Fig. 4.

Using the relation for thermal life, a prognosis of thermal life for transformer oil is obtained and presented in Table 4.

Table 4. Thermal lifetime, in hours, with different ageing criteria.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Loss factor</th>
<th>Neutralization index</th>
<th>Interfacial tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>60ºC</td>
<td>263</td>
<td>148</td>
<td>133</td>
</tr>
<tr>
<td>80ºC</td>
<td>114</td>
<td>397</td>
<td>367</td>
</tr>
<tr>
<td>100ºC</td>
<td>4933</td>
<td>1062</td>
<td>1158</td>
</tr>
<tr>
<td>120ºC</td>
<td>2179</td>
<td>284</td>
<td>396</td>
</tr>
</tbody>
</table>

The thermal lifetime values obtained using the relation (24) are in good correlation with obtained experimental data.

4 Conclusion
In the framework of this paper, a method for establishing the thermal lifetime of the electroinsulating oil as part of transformer lifetime is proposed. With proposed experimental data, the
model was verified for the case in which the ageing criteria are the loss factor, the neutralization index and the interfacial tension.

Regarding the accelerated thermal tests, some notes can also be underlined:
- The loss factor did not reach the criterion of end of life, but, the neutralization index and the interfacial tension reached these criteria;
- The thermal lifetime values at the temperatures of 100°C are the highest values with the loss factor degradation criteria and the lowest values if the criterion is the neutralization index;
- The brusquest diminution of the lifetime during the rise of the temperature is noticed in the case of the degradation criterion - neutralization index, and the slowest diminution, in the case of the degradation criterion - loss factor;
- The life times of the oils resulted following the accelerated ageing tests at the temperature of 100°C range between 1.35 years for the loss factor degradation criterion, and 0.75 for the neutralization index degradation criterion;
- The relatively great distances between the life durations of the oils may have different causes among whom, there should be mention: different sensitivity of the degradation criteria, accurate choice of the criteria of end of life, influence of the conditions of experimentation;
- The shape of the thermal lifetime graphs of the transformer oil in coordinates (1/T, lgL) resorting to the three degradation criteria is almost linear. This fact proves that the degradation mechanism of the oil can be considered of the Arrhenius type.

References: