Fuel 117 (2014) 756–762

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# Method for lifetime estimation of power transformer mineral oil

Laurentiu Marius Dumitran [a,*], Radu Setnescu [b,c,*], Petru V. Notingher [a], Laurentiu Viorel Badicu [a], Tanta Setnescu [b,c]

[a] Laboratory of Electrical Materials, University Politehnica of Bucarest, Splaiul Independentei, No. 313, 060042 Bucharest, Romania
[b] Valahia University of Targoviste, Bd. Unirii 18-22, 130082 Targoviste, Romania
[c] National Institute for R&D in Electrical Engineering (ICPE-CA), Splaiul Unirii No. 313, 030138 Bucharest, Romania

## HIGHLIGHTS

- The paper proposes a simpler and faster method for mineral oil lifetime estimation.
- The proposed method is based on a single ageing test at higher temperature and the activation energy obtained by DSC.
- The obtained results well agree with those derived from the present standardized method.
- The proposed method is effective in terms of costs and experimental time.

## ARTICLE INFO

*Article history:*
Received 30 March 2012
Received in revised form 27 September 2013
Accepted 1 October 2013
Available online 17 October 2013

*Keywords:*
Mineral oil
Thermal ageing
Lifetime estimation
Activation energy

## ABSTRACT

Large amounts of mineral oil are used in electrical equipments as insulation and cooling medium. To avoid damages and cut-off of power electricity supply it is necessary to evaluate the mineral oil condition. Lifetime estimation of mineral oil which is based on accelerated thermal ageing at three temperatures (according to IEC 60216-1/2001) requires a long experimental time. This standardized method permits the lifetime calculation using a model based on the equation $\ln D(T) = a + \frac{b}{T}$, where $a$ is the intercept and the slope of the plot $\ln \tau_x$ versus $1/T$, $b$ is a material constant, $T$ is the accelerated ageing temperature and $\tau_x$ is the time to reach the acceptable limit value of a chosen degradation parameter. In the present paper, mineral oil lifetime at 80 °C ($D_1 = 1.53 \times 10^5$ h) has been obtained on the basis of accelerated ageing tests at three different temperatures (115 °C, 135 °C and 155 °C) and choosing the oil electrical resistivity ($\rho$) as degradation parameter. The activation energy of the ageing process determined in these conditions was 101.8 kJ/mol.

To reduce the test duration, this paper proposes a simpler method based on a single ageing test at a higher temperature and the activation energy of the oxidation reaction being determined from non-isothermal Differential Scanning Calorimetry (DSC) measurements. According to the proposed method, the plot $\rho$ versus $\tau$ (ageing time) was drawn only for the accelerated ageing temperature $T = 155$ °C and the lifetime value ($\tau_x$) for this temperature was experimentally obtained. In this case, the activation energy value $E_a$ corresponding to oxidation reaction was determined ($E_a = 102.4$ kJ/mol). Based on both $E_a$ and the $\tau_x$ at 155 °C, the lifetime at 80 °C ($D_2 = 1.86 \times 10^5$ h) was determined and compared with $D_1$. The differences between $D_1$ and $D_2$ values are acceptable and the proposed method is effective in terms of costs and experimental time (the experimental time is reduced by a factor of 12–14) as compared to the present standardized method.



## 1. Introduction

The power transformers which operate in electric energy distribution and transmission grids have the insulation systems made in cellulose paper and mineral oil. The mineral oil represents 70–80% of the insulation system weight which means, for example, about 80 thousands liters in the case of a 150 MVA transformer [1]. During the operation, both cellulose paper and oil are subjected to electrical, mechanical, thermal and environmental time variable stresses and leading to the worsening of the electrical properties of the mentioned materials. Moreover, there are several power transformers which have been installed more than 30 years ago presenting different ageing levels of their insulation systems; hence they might fail at any time [2]. It is known that the failure

* Corresponding authors. Address: Valahia University of Targoviste, Bd. Unirii 18-22, 130082 Targoviste, Romania (R. Setnescu), Laboratory of Electrical Materials, University Politehnica of Bucarest, Splaiul Independentei, No. 313, 060042 Bucharest, Romania. Tel.: +40 214039285 (L.M. Dumitran).
*E-mail addresses:* dumitran@elmat.pub.ro (L.M. Dumitran), rsetnescu@yahoo.com (R. Setnescu).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.10.002

of a power transformer causes significant expenditures related to its reparation or replacement as well as financial losses compensations required by consumers. Therefore, power transformers users must know as much as possible the remaining lifetime of their equipment in order to take the best decisions concerning the equipment maintenance, refurbishment or replacement [3,4].

Several methods for the diagnosis of the transformers insulation systems, based on the elapsed exploitation time have been proposed. The remaining lifetime can be calculated and an efficient management avoiding the early failures and extending the transformers lifetime (by different maintenance procedures, such as oil refurbishment) can be developed [5–14]. Generally, these methods are based on the analysis and monitoring of some physico-chemical characteristics of both oil and paper subjected to high temperatures, water, oxygen, electrical discharge, vibrations, etc. [11–14]. The estimated lifetime of oil and paper, determined before the transformer start up, are taken also into account by these methods.

Generally it is accepted that heat is the most important stress factor that induces the degradation of an insulation systems during the transformers service. Assuming that the thermal stress is preponderant, the most commonly used method for insulations lifetime assessment is based on accelerated thermal ageing tests at three temperatures (see for example IEC 60216-1/2001 [15]). In case of transformer oil and paper these temperatures range between 110 and 160 °C [16]. Unfortunately, the accelerated thermal ageing method is time-consuming especially for thermal ageing temperatures close to the operation conditions (for example, an ageing test at $T$ = 115 °C requires about one year).

It is known that the hydrocarbon compounds (like simple hydrocarbons, mineral oils or hydrocarbon polymers) are unstable under the influence of elevated temperatures, especially, in the presence of oxygen. Generally, the oxygen can degrade the hydrocarbons by processes based on free radicals reactions which generate hydroperoxides [16]. The hydroperoxides are unstable and decompose to other free radicals leading finally to water and ketones as well as to different other oxidation products, such as carboxylic acids alcohols and phenols. Different gaseous (such as CO, $CO_2$, and low molecular mass hydrocarbons), liquid (e.g. acids, ketones, alcohols, tars and water) and solid phase products (e.g. asphalts and carbenes) were identified as oxidation products of hydrocarbon oils [17]. An oxidation mechanism and discussion related to this topic is presented in Ref. [20].

The presence of these oxidation products, leads to the increase of water absorption and to the worsening of the useful properties of the hydrocarbon based materials [17,18]. In case of transformer mineral oils, the solid phase oxidation products (sludge) may block the oil circulation ways and deposit on the transformer's windings and tank, making difficult the heat transfer [17–19]. The carboxylic acids dissolved in the oil have a negative effect on the paper insulation and conductors of the windings, while the volatilized acids can produce corrosion attack on the top part of the transformer.

This paper presents a simpler and time effective method for lifetime estimation of transformers mineral oil, which assumes that the thermo-oxidative reaction is the preponderant reaction of oil degradation during transformers operation. This method is based on the assessment of the activation energy of oxidation reaction by Differential Scanning Calorimetry (DSC) and a single accelerated thermal stress test at a relatively high temperature (155 °C).

## 2. Experimental

### 2.1. Materials

The mineral oil used in this study was of type Mol To 30.01R (produced by Mol Lub Hungary Kft.) which is a mineral oil without antioxidant additives, special manufactured for power transformer insulation systems. The product contains 53.1% paraffinic carbons, 39% naphthenic carbons and 7.1% aromatic carbons and has 2-furfural content lower than 0.1 mg/kg. It was kindly supplied by Mol Romania Petroleum Products® and it was used without any supplementary conditioning.

### 2.2. Methods

Accelerated ageing experiments were performed at different temperatures, namely $T_1$ = 115 °C, $T_2$ = 135 °C and $T_3$ = 155 °C using an oven with forced air circulation. In view to perform the accelerated thermal ageing, the oil was placed in sealed glass cells. At different time periods, the aged oil samples were taken-out and the absorption/resorption currents were measured using a Keithley 6517 electrometer and a special IRLAB liquids cell.

The oil resistivity ($\rho$) has been calculated from the measured absorption currents (according to IEC 60247) based on the following expression:

$$\rho = \frac{U_0}{i_a(60)} \frac{S}{d}, \quad (1)$$

Were $U_0$ = 300 V is DC applied voltage, $d$ is the distance between the electrodes of the cell and $S$is the electrodes area. $i_a(60)$ represents the absorption current value measured after 60 s from the initial applied voltage moment [40].

DSC (Differential Scanning Calorimetry) measurements were performed in non-isothermal mode (constant heating rate) on a Setaram 131 EVO apparatus, in the following conditions: sample weight 3.9 ± 0.7 mg, air flow 50 mL/min, aluminum pans of 100 μL capacity, temperature range 30–310 °C and heating rate of 2, 4, 6 or 10 °C/min.

Because the oil was fairly volatile and evaporated before oxidation, the sample containing pans were capped by lids which suppressed the evaporation process. A volume of around 70 μL of air was present in each pan enabling the oxidation process in static atmosphere. An example of a DSC curve is shown in Fig. 1. The oxidation onset temperature (OOT) was calculated, according to ASTM E2009-02 [21] as the intersection point of the recorded baseline and the slope of the oxidation exotherm, using the specific function of Calisto Data Processing (Setaram Inc.) software. The $T_{0.6}$ parameter was calculated as the temperature at the 0.6 of the oxidation peak height (Fig. 1). The thermal effect ($\Delta H_{ox}$) and the peak temperature of exotherm oxidation peak ($T_m$) were calculated using the integration function.

The activation energy of oil oxidation has been evaluated from DSC measurements, using the onset of the oxidation peak at ~185 °C (Fig. 1). The values of the $T_{0.6}$, or heating rate ($\beta$) were

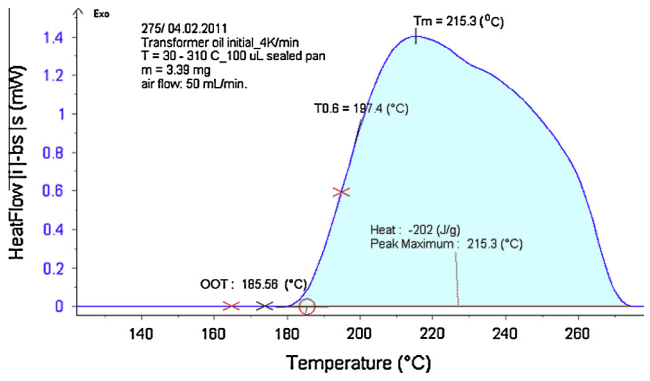


**Fig. 1.** DSC curve of the mineral oil (heating rate 4 K/min.) and determination of the oxidation kinetic parameters.