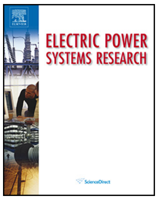
Electric Power Systems Research 151 (2017) 1–11

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Assessing degradation of power transformer solid insulation considering thermal stress and moisture variation

Ricardo D. Medina[a,b,*], Andrés A. Romero[b], Enrique E. Mombello[b], Giuseppe Rattá[b]

[a] Grupo de Investigación en Energía GIE, Universidad Politécnica Salesiana Sede Cuenca, Calle Vieja 12-30 y Elia Liut, Cuenca EC 010102, Ecuador
[b] Instituto de Energía Eléctrica, Universidad Nacional de San Juan, IEE – UNSJ – CONICET, Av. Libertador San Martín, 1109 (o), San Juan, J5400AR, Argentina

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 6 April 2017
Accepted 7 April 2017

Keywords:
Brownian random process
Insulation ageing
Life estimation
Oil-paper insulation
Paper moisture
Power transformer

ABSTRACT

This paper presents a novel method for estimating the degradation of solid insulation in power transformers, considering thermal ageing and paper moisture dynamics. Current ageing models are based on both, experimental evidence and theoretical developments; considering that all models are approximation to reality, loss of life estimation could be found in a large range depending on the evidence considered; this amplitude could lead inaccurate results to make adequate decisions in an asset-management context. These differences in results can be explained because the models consider only nominal operative temperatures ranges overlooking low and high temperatures degradation process and the influence of variations in paper moisture content. Considering the above, this document proposes a holistic methodology for solid insulation ageing assessing based on all thermal degradation process (oxidation, hydrolysis and pyrolysis) and the influence of dynamics on paper moisture. Paper moisture is estimated using as input external variables such as: load, ambient temperature, transformer technical data and measurements regarding oil moisture, in order to consider uncertain in oil moisture growing Arithmetic-Brownian-Motion algorithms are presented. The proposed methodology was tested for four power transformers, for which load and ambient temperature hourly profiles are available over a period of almost nine years. In order to compare different degradation rates, three alternatives to model the chemical environment in which cellulose is aged, are analysed. Results are presented, and conclusions are finally detailed.

1. Introduction

Solid insulation failure is the leading cause of the end-of-life of power transformers (PTs) [1]. Therefore, a measure of the state of the solid insulation (paper) is accepted as an indicator of the PT condition [2]. Paper is composed by long chains of glucose rings that build the cellulose polymer molecule. The average length of these chains is termed degree of polymerization (*DP*). During the PT life cycle, *DP* decreases due to ageing processes (i.e., oxidation, hydrolysis and pyrolysis) [3], and consequently insulating paper loses its dielectric and mechanical properties.

Degree of polymerization can be directly measured from a sample of paper, but this practice for a PT in operation implies a non-desired disconnection and an invasive manipulation of the unit. Therefore, computational methods for indirect estimation of *DP* value (that is related with the loss-of-life) can be used as an alternative. For instance, according to IEEE C57.91 [4], the paper loss-of-life is assessed as a function of the hot spot temperature (θ_{HS}) during a time period, Δt, of PT operation. Such approach considers that heat is the main ageing agent, and assumes that both humidity and acidity content in the oil-paper insulating system remain constant.

The following Arrhenius relation is widely accepted to model the ageing of paper [5].

$$\frac{1}{DP(t)} - \frac{1}{DP(t_0)} = A \cdot e^{\frac{E_a}{R \cdot T(t)}} \cdot \Delta t \tag{1}$$

where $DP(t_0)$ and $DP(t)$ are *DP* values at the start, t_0, and at the end, t, of the analysed time interval Δt; E_a is the activation energy of the ageing reaction, expressed in [J/mol]; A is the pre-exponential factor and it depends on the chemical environmental; R is the gas constant (8.314 [J/mol/K]); and T is the temperature of the paper in [K], that is just θ_{HS} in the top of the windings, because at this place occurs the highest paper degradation in a PT [6].

A post-mortem evaluation of a PT was performed in order to validate the Arrhenius models in Ref. [6]. The main conclusion of

---

[*] Corresponding author at: Grupo de Investigación en Energía GIE, Universidad Politécnica Salesiana Sede Cuenca, Calle Vieja 12-30 y Elia Liut, Cuenca EC 010102, Ecuador.

E-mail address: rmedina@iee.unsj.edu.ar (R.D. Medina).

http://dx.doi.org/10.1016/j.epsr.2017.04.006
0378-7796/

this work are that the available *A* and *E* values are not sufficiently accurate to estimate *DP*, because they do not include the combined effects of moisture, acidity and oxygen.

In Ref. [7], the thermal life expectancy of a fleet of 185 PTs was estimated. For this purpose, Eq. (1) was employed but assuming different values for *A*, in order to account for oxidation and hydrolysis processes. However, it was assumed that moisture content in paper is a discrete function of *DP* value. In fact, it was assumed that moisture content is 1.0, 1.5 and 2.0% within the DP range of 1000–500, 500–250 and 250–200. The average life expectancy of 185 transformers was quantified as 83 years.

In Ref. [8], general lines for power transformer asset management are proposed. Transformer administration considers condition monitoring, maintenance plans and ageing assessment. Condition takes into account: vibration analysis, partial discharge, frequency response analysis (FRA) and thermal analysis. Thermal analysis is based on following tests: *DP*, furans, paper retailed tension and thermal ageing.

In Ref. [9], a computational platform for data integration and an intelligent system for fault detection and diagnosis as well reliability for PT is presented. This tool uses as input: top-oil-temperature, FRA and dissolved gas analysis.

In Ref. [10], the authors presents an approach for calculating the thermal lifetime of transformer insulation using Montecarlo techniques in order to consider uncertain in load and ambient temperature artificial history. Thermal ageing is the most relevant agent in insulation degradation.

In Ref. [11], an updated method to calculate remaining life of power transformer solid insulation was presented. The research was conducted during a period of three years, over three single-phase 4 kV A–2 kV/230 V transformers that ran at high load and reached the end of insulation life. In order to compare estimated and real degradation, samples of oil and paper were taken along the experiment, and *DP* and water content were measured, along with the gas content of the oil. Main finding of such research are: (1) the activation energy value, $E_a = 111$ kJ/mol, proposed in Ref. [12] is probably almost right; (2) proposed equations for modelling the relationship between oxygen and paper moisture with the factor *A*, which was assumed to be independent of the temperature, are in a good agreement with the experimental evidence; and (3) it is improper to use a numerical average of temperature profiles since the relationship between the temperature and the reaction rate is not linear. It must be noted that the accelerated ageing experiment performed considers only hydrolysis, thus passing over low temperature degradation phenomena. In this work, paper moisture influence is emphasised, but no practical evaluation method is proposed.

In Ref. [13], models for estimating residual operative time of transformer oil are presented, these models are based on artificial neural networks and non-linear models and works with statistical information. Application of these models predicts oil characteristics and can help effective PT management.

From the above brief review, it is concluded that an advanced model for estimation of the insulation paper degradation of a PT in operation, must suitably consider dynamics in both the paper temperature, θ_{HS}, and the chemical environment, *A*. As was stated, in Eq. (1), *DP* depends on θ_{HS}, which can be directly measured or mathematically approached. For instance, θ_{HS} in a PT can be measured by using fibre-optical thermocouples installed at the windings or estimated using e.g., a set of differential equations. Similarly, the *A* factor depends on the presence of water, oxygen and acids, that can be also directly measured or computationally estimated.

In practice, aged PT does not have pre-installed thermocouples, and direct measures of water content in paper are not usually performed. In order to overcome this limitation, the main contribution of this paper can be summarised as follows:

(1) Proposal of a practical methodology for computational estimation of *DP* and the loss of life.
(2) The proposal takes into account both hot spot temperature and chemical environment variations, which are modelled considering uncertainty and lack of information.
(3) Proposed method add information on life-span estimations.

The novelty of this proposal is just a methodology which integrates several pieces of evidence (e.g., paper moisture content interaction with paper ageing, paper and oil moisture relationship, paper moisture and temperature relationship, influence on ageing of oxidation, hydrolysis and pyrolysis, etc.) reported in literature, that have not been connected until now.

This article has been organised as follows. Section two describes the following topics: solid insulation degradation process, θ_{HS} estimation, evaluation of water content in paper and loss of life computation. Section three describes the proposed methodology. Section four presents the obtained results after applying the proposed method by using acquired data from four units currently in operation. Finally, conclusions are given in section five.

2. Theoretical framework

Paper is used in oil-cooled PTs as insulating material due to its excellent dielectric and mechanical properties. Meanwhile, oil degradation can be managed by treatment methods as dehumidification, purification and filtration, or even by oil replacement; there are not paper refurbishment methods.

Therefore, paper is one of the most critical insulating materials in a PT [14]. A well-known indicator to measure the condition of paper is the aforementioned *DP*, which value decreases when paper is exposed to water, oxygen, heat and acids. It is widely accepted that *DP* value is in the range of 1200–1000 at the beginning of the transformer life. In a *DP* range between 1000–500, the mechanical strength of paper remains almost constant. Mechanical strength of paper decreases proportionally to *DP* value in the range 500–200. Finally, when *DP* value is lower than 200–150, paper is not able to withstand mechanical stresses; in fact, the mechanical strength of paper can be reduced to 20% of its initial strength, which is usually assumed to be the end-of-life criterion for power transformer insulation [15].

2.1. Ageing of cellulose

Cellulose ageing processes act simultaneously and synergistically; consequently, to achieve a good model is a very complex task. Nevertheless, for practical purposes most researchers and organizations assume three independent degradation processes: oxidation, hydrolysis and pyrolysis, each one acting in a specific temperature range.

In Ref. [16], the general Arrhenius relation expressed in Eq. (1) was disaggregated in order to consider hydrolysis, oxidation and pyrolysis, as:

$$\frac{1}{DP\left(t\right)} - \frac{1}{DP\left(t_0\right)} = \sum\nolimits_{t_0}^{t} k\left(t\right)\cdot\Delta t \tag{2}$$

with:

$$\begin{aligned} k\left(t\right) = \Big(& A_{oxi}\left(t\right)\cdot e^{\frac{-E_{a,oxi}}{R\cdot(273+\theta_{HS}(t))}} + A_{hyd}\left(t\right)\cdot e^{\frac{-E_{a,hyd}}{R\cdot(273+\theta_{HS}(t))}} \\ & + A_{pyr}\left(t\right)\cdot e^{\frac{-E_{a,pyr}}{R\cdot(273+\theta_{HS}(t))}}\Big) \end{aligned} \tag{3}$$

where *k(t)* is the degradation rate and *oxi*, *hyd* and *pyr* subscripts correspond to oxidation, hydrolysis and pyrolysis respectively.

2.1.1. *Oxidation of cellulose*

Oxidation is the combination of paper and oil with oxygen. This reaction increases the acidity of the medium. It is predominant at temperatures below 60–75 [°C]. This means that the insulating paper of an unloaded PT is mainly degraded by acidification. In Refs. [17] and [18], it was found that the activation energy, $E_{a,oxi}$, is lower for oxidation than for hydrolysis. Oxidation sub-products are CO, CO_2 and H_2O. According to Ref. [19], from the oxidation point of view, thermally upgraded papers (TUP) do not offer great advantages regarding non-thermal upgraded papers (No-TUP).

2.1.2. *Hydrolysis of cellulose*

This process requires heat, water and an acid environment to trigger the paper degradation. Hydrolysis is the main degradation process in the range 70–130 [°C]; it produces H^+ ions, CO, CO_2, and furans in No-TUP. TUP ages 1.5–3 times slower than No-TUP [19].

2.1.3. *Pyrolysis of cellulose*

Pyrolytic degradation is produced exclusively by heat. Its activation energy, $E_{a,pyr}$, is 1.4–2 times bigger than hydrolysis $E_{a,hyd}$. Pyrolysis is the main degradation process above 130 [°C] and, starting at 140 [°C] it becomes a self-accelerated reaction through water and oxygen generation [20].

2.2. *Degradation accelerators*

2.2.1. *Temperature*

Temperature inside a PT is not uniform. Hot spot temperature (θ_{HS}), expressed in [°C], is located at the top of the tank, over the windings. θ_{HS} is a function of load, ambient temperature, and constructive features of the unit. In Ref. [21], a dynamic model for θ_{HS} estimation was proposed. The model is based on the solution of the following two differential equations:

$$\left(\frac{(1+R\cdot {K_L}^2)}{(1+R)}\cdot {\mu_{pu}}^n\cdot \Delta\theta_{TO,R}\right)=\left({\mu_{pu}}^n\cdot \tau_{TO,R}\cdot \frac{d\,\theta_{oil}}{d\,t}\right)+\frac{(\theta_{TO}-\theta_{amb})^{n+1}}{{\Delta\theta_{TO,R}}^n} \tag{4}$$

$$\left(\left\{K^2\cdot P_{W,pu}\left(\theta_{HS}\right)\right\}\cdot {\mu_{pu}}^n\cdot \Delta\theta_{HS,R}\right)=\left({\mu_{pu}}^n\cdot \tau_{W,R}\cdot \frac{d\theta_{HS}}{dt}\right)+\frac{(\theta_{HS}-\theta_{TO})^{m+1}}{{\Delta\theta_{HS,R}}^m} \tag{5}$$

where θ_{TO} is the top oil temperature, R is the ratio between load and no-load losses, K_L is the load factor, μ_{pu} is the oil viscosity in pu, n is a constant that depends on oil circulation, m is an empirical constant taken from IEEE Loading Guide-Annex G [4]. $\Delta\theta_{TO,R}$ is the rated top-oil θ_{TO} rise above the ambient temperature, $\Delta\theta_{HS,R}$ is the rated hot-spot temperature above the top-oil temperature, $\tau_{TO,R}$ is the rated thermal time constant, $\tau_{W,R}$ is the rated winding time constant and θ_{amb} is the ambient temperature. Further explanations about the constants n and m related to oil viscosity variation can be found in Refs. [21] and [22].

Solving simultaneously Eqs. (4) and (5) for each interval i, $\theta_{HS,i}$ is obtained and can be used to calculate the de-polymerization by using Eqs. (2) and (3).

2.2.2. *Humidity*

Water accelerates the insulating paper ageing [11]. PT are dried during the manufacturing process. The moisture content of the insulation system will continually increase afterward. The main sources of water contamination are: (i) air intake from atmosphere, (ii) oil-paper decomposition and, (iii) residual humidity not removed during factory drying procedure. Water content in paper can be measured from a paper sample by using Karl Fischer titration, or inferred by using frequency-domain spectroscopy [23]. However, in practice, for most PTs currently in operation, neither direct measurements nor dielectric response analysis (which is in some way a recent test technique) are usually performed. Nevertheless, physical–chemical oil testing analysis is a common and frequent practice [24]. Therefore, historical data about water content in oil is available and it can be used to deal with the above drawback.

In this regard, mathematical relations that have been established in order to approach water content in paper, can be used. For instance, ABB paper humidity formula, presented in Eq. (6), is an empirical function that relates water content in paper to water content in oil and θ_{HS}, assuming equilibrium conditions [25].

$$H_p=2.06915\cdot e^{(-0.0297\cdot\theta_{HS})}\cdot (H_o)^{0.4089\cdot{\theta_{HS}}^{0.09733}} \tag{6}$$

where H_p is the paper moisture, expressed in [%], and H_o is the oil humidity expressed in [ppm].

The time to reach thermal equilibrium is around several hours to a few days [26]. This condition is not reached in normal operation PT, because both load and ambient temperature vary during the day. In order to overcome this situation, it is possible to consider that PTs work under daily and weekly cyclic load profile, this produces a cyclic θ_{HS} profile, then, paper moisture adsorption/desorption oscillates around an equilibrium point or area. This idea has been verified in Ref. [27] for the range of operative temperatures of the unit. Therefore, a practical way to determinate water in transformer paper insulation is to use ABB formulation with water content in oil and a smoothed θ_{HS} profile. Some smoothing methods are proposed in the state of the art: in Ref. [28] a daily average is recommended, in Ref. [29] a long term average is proposed, in Ref. [30] a three day average is computed, and in Ref. [31] the daily moisture concentration of cellulose is calculated by averaging the maximum and minimum moisture during one day interval. Long term averages for temperature may provide an estimate of the bulk cellulose water content. However, its use will not detect fluctuations in the surface of cellulose nor thin structures moisture, in Ref. [28] the authors recommends use of dynamic models for determining H_p based on daily measurements. Considering previous evidence, in this work a daily average was selected due the suppression of hourly variation.

A sophisticated method have been developed to estimate paper water content for no-equilibrium conditions [28], nevertheless this model requires additional information about physical–chemical characteristics of the paper and oil. When this information is available, it is advisable to use that model. Otherwise, Eq. (6) can be used. A method to estimate oil moisture is proposed in Section 3.2.

2.2.3. *Chemical environment*

In Eqs. (1) and (2), the pre-exponential factor A represents the environmental influence on the degradation rate *k(t)*. Many accelerated ageing experiments have been performed in order to quantify the relationship between humidity, heat and paper condition.

For instance, in Refs. [32] and [33], the following quadratic equations that relates A_{hyd} value, paper moisture and oxygen were presented: for No-TUP (7), and (8) for TUP. Oxygen ranges are:

Table 1
$E_{a,oxi}$ and A_{oxi}.

	No-TUP		TUP
Author	Feng	Lelekakis	Lelekakis
$E_{a,oxi}$ [kJ/mol]	89	89	82
A_{oxi}	4.6×10^5	4.6×10^5	3.2×10^4

Table 2
E_{pyr} and A_{pyr}.

Author	Conesa	Capart	Kashiwagi
$E_{a,pyr}$ [kJ/mol]	215.7	255	220
A_{pyr}	4×10^{17}	5.8×10^{20}	7.2×10^{20}

low content (<7000 ppm), medium (7000–14,000 ppm) and high content (>16,500 ppm).

$$A_{hyd} = \begin{cases} 1.78 \cdot 10^8 \cdot {H_p}^2 + 1.1 \cdot 10^8 \cdot H_p + 5.28 \cdot 10^7 & \rightarrow \text{Low } O_2 \\ 2.07 \cdot 10^8 \cdot {H_p}^2 + 5.61 \cdot 10^8 \cdot H_p + 2.31 \cdot 10^8 & \rightarrow \text{Med } O_2 \\ 2.29 \cdot 10^8 \cdot {H_p}^2 + 9.78 \cdot 10^8 \cdot H_p + 3.86 \cdot 10^8 & \rightarrow \text{High } O_2 \end{cases} \tag{7}$$

$$A_{hyd} = \begin{cases} 6.92 \cdot 10^7 \cdot {H_p}^2 + 2.61 \cdot 10^8 \cdot H_p + 1.03 \cdot 10^7 & \rightarrow \text{Low } O_2 \\ 2.64 \cdot 10^8 \cdot {H_p}^2 + 7.32 \cdot 10^8 \cdot H_p + 2.37 \cdot 10^9 & \rightarrow \text{Med } O_2 \\ 4.29 \cdot 10^8 \cdot {H_p}^2 + 2.03 \cdot 10^9 \cdot H_p + 4.27 \cdot 10^9 & \rightarrow \text{High } O_2 \end{cases} \tag{8}$$

where H_p is the paper moisture, expressed in [%].

Considering that, it is desirable to maintain low oxygen levels for units in service [16]. If oxygen content is high, there are some possible actions as: add oxygen inhibitors into oil or to conduct a degasification process. For most common service conditions, it is recommendable to use low oxygen equation.

The value of A_{hyd} computed through the above expressions is considered to be used directly in Eq. (1). However, as previously mentioned, according with empirical evidence [18], at low and high temperatures oxidation and pyrolysis are respectively the most significant degradation processes. Therefore, if the aim is to model together all three degradation processes in solid insulation loss of life, as in the case of the approach proposed in this paper, then, Eqs. (2) and (3) must be used.

Values for $E_{a,ox}$ and A_{ox} were obtained by Feng et al. [7] and Lelekakis et al. [32]. These values are reported in Table 1. For pyrolysis, $E_{a,pyr}$ and A_{pyr} values can be found in the works of Conesa et al. [34], Capart et al. [35] and Kashiwagi and Nambu [36] and, these are presented in Table 2.

2.3. Estimation of paper loss of life

1) DP based remaining life

In Ref. [37], the following relationship between *DP* and loss of life for No-TUP units was proposed.

$$\%Life_{Loss} = {[\log_{10}(DP) - 2.903]}/{-0.006021} \tag{9}$$

Furthermore, the following equation for TUP was introduced in Ref. [38].

$$\%Life_{Loss} = 100 \cdot \left(-0.881 \cdot \ln\left({DP}/{622}\right)\right) \tag{10}$$

Both equations are similar, since considers *DP* = 200 as the end-of-life criterion. The main difference is the degradation beginning value, since it was assumed that the paper begins to get degraded at *DP* = 820 in Eq. (9), and such initial value was *DP* = 622 in Eq. (10).

2) Time based remaining life

The percentage of loss-of-life proposed in IEEE Loading-Guide C.57.91 [4] is shown in Eq. (11), and it represents the relation between consumed life and normal insulation life. The value of normal life is 150,000 h at standard conditions, i.e., at rated hot spot temperature and constant humidity, it corresponds to the time to reach a DP value equal to 200.

$$\%Life_{Loss} = \frac{F_{AA}}{\text{Normal insulation life}} \times 100 \tag{11}$$

$$F_{AA} = \sum_{i=1}^{n} e^{\frac{15000}{\theta_{HSR}+273} - \frac{15000}{\theta_{HS_i}+273}} \cdot \Delta t_i \tag{12}$$

where, F_{AA} is the ageing acceleration factor, θ_{HSi} is the hot spot temperature for each interval *i*, θ_{HSR} is the rated hot spot temperature: 98 °C for no thermal upgraded papers and 110 °C for thermal upgraded paper, θ_{HSi} is the hot spot temperature for ever Δt_i time interval.

3. Problem description and proposed methodology

3.1. Problem description

As it was mentioned in the previous sections, in practice, direct measurements of θ_{HS} and water content in paper are not available, especially in the case of old transformers. As the historical evolution of these two parameters is needed to suitably estimate the solid insulation degradation of a PT by means of the Arrhenius relation; then, the aim of this paper is to present a robust methodology for the indirect estimation of insulating paper loss-of-life. The proposed method is able to account for the moisture influence and the low and high temperature degradation processes in the thermal ageing model.

3.2. Oil moisture estimation method

As it was noted before, to assess the DP value, the historical evolution of the water content in paper is needed. In this section, a method to generate this paper moisture profile is proposed. The method uses historical information of the unit, or even, in absence of any measure, data is extracted from power transformer surveys.

If the unit owner has historical data of water content in oil, it is possible to analyse tendencies and forecast humidity evolution in paper. If such information is not available, and assuming that the unit has a good sealing, it is possible to estimate the amount of water contamination inside the tank using empirical values to create probable profiles.

Oil humidity variations inside power transformers satisfy the following conditions: (i) stochasticity, (ii) continuity, (iii) temporal independence, (iv) self-similarity and, (v) is a memoryless process. Therefore, oil humidity content can be approached by using the generalised Wiener Process, also called Arithmetic Brownian Motion (*ABM*) [39]. The corresponding mathematical formulation is:

$$Z_t^{(m)} = Z_{t-1}^{(m)} + \mu \cdot \Delta t + \sigma \cdot \sqrt{\Delta t} \cdot X_n \tag{13}$$

where $Z_t{}^{(m)}$ is the t^{th} term of the *m* path, μ is the expected value, σ is the standard deviation, Δt is time period *T* divided in *N* equal intervals and X_n is Gaussian white noise $N(0,1)$. For all paths, there is only one initial value, that is, there exists exactly one Z_0 for all *m*.

If there are two or more known points, it is possible to create a Brownian Bridge (BB) assuming that the uncertainty is zero in these points or nodes, for all paths, the maximum uncertainty is in the middle of two know points. The increments in BB are not independent. The corresponding equation is Eq. (14), where $BZ_t{}^{(m)}$ is the t^{th} term of the m path between the two known points W_n and W_{n+1} with ($t_n < t < t_{n+1}$), σ is the standard deviation, and X_n is the Gaussian white noise $N(0,1)$. There are common points for all

Table 3
Characteristics of studied units.

	T1	T2	T3	T4
Rated power [MVA]	30/30/20	30/30/20	15	30/30/20
Voltage [kV]	132/34,5/13.8	132/34,5/13.8	132/34,5	132/34,5/13.8
Connections	Yy0/Yd11/Yd11	Yy0/Yd11/Yd11	YNy0	Yy0/Yd11/Yd11
Cooling class ONAN/ONAF	0–70%/70%–100%	0–70%/70%–100%	0–70%/70%–100%	0–70%/70%–100%
Year of manufacture	1969	1994	1963	1984

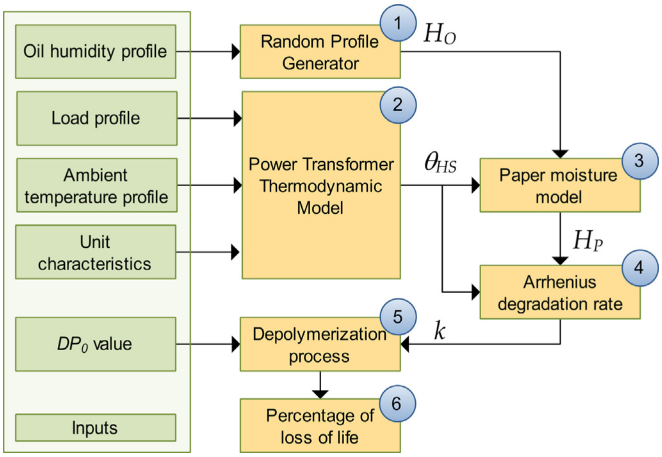


Fig. 1. Proposed loss-of-life methodology.

paths, that is, there exists exactly one W_n. for all m.

$$ZB_t^{(m)} = \left[W_n + \frac{t-t_n}{t_{n+1}-t_n}\left(W_{n+1}-W_n\right)\right] + \sigma \cdot \sqrt{\frac{(t-t_n)\cdot(t_{n+1}-t)}{t_{n+1}-t_n}} \cdot X_n \tag{14}$$

ABM will be used when limited or no oil moisture information is available, in the other hand, *BB* considers uncertainties when some data exist.

3.3. *New degradation estimation approach*

Fig. 1 shows a methodology to assess the degradation of a power transformer considering thermal stress and paper moisture; every step is numbered and described in detail in the following:

Step 1. Generation of random oil humidity profiles for the analysis period, this information is needed in order to model moisture dynamics and water migration from oil to paper. Oil humidity depends on sealing quality of the unit and environmental conditions.

There are two forecast alternatives: (a) if there are some water in oil historical records, then use Eq. (14); otherwise, (b) use Eq. (13) with statistical information.

Step 2. Calculation of θ_{HS} solving simultaneously Eqs. (4) and (5); the transformer characteristics, load and ambient temperature profiles are required as inputs.

Step 3. Estimation of hot-spot paper moisture using Eq. (6) with smoothed θ_{HS} profile, and oil humidity profiles as inputs. It is important to consider that estimated paper moisture corresponds to the most degraded point of the windings, where the temperature is the highest.

Step 4. The degradation rate *k(t)* is computed using Eq. (3). A_{oxi} and E_{oxi} values are taken from Table 1. Considering that A_{pyr} and E_{pyr} values were experimentally obtained, the average value describes well pyrolysis degradation, mean values are taken from Table 2, A_{hyd} value is estimated with Eq. (7) for No-TUP and Eq. (8) for TUP. $E_{a,hyd}$ is 111 [kJ/mol].

Table 4
Reported oil moisture content, in [ppm].

Date	T1	T2	T3	T4
January 2008	16.7	4.8	16.2	8.5
July 2008	17	5	16	8.6
July 2009	18	7	17	9
May 2011	18.5	6	18.7	9.7
January 2013	19.2	8	20	11.8
February 2014	19.9	7.6	20.6	12.6
January 2015	20.5	7.4	21	13.2
May 2016	21	7	22	13

Step 5. Assessment of depolymerization using Eq. (2) where $DP_0 = 1000$ corresponds to a new unit; for old units is possible to use a DP_0 value derived from other sources e.g. furan analysis or direct sample measure.

Then, a set of final degree of polymerization values are obtained, the probable DP final value is obtained by calculating the average value of final DP value of all random simulations.

Step 6. Estimation of loss-of-life using Eq. (9) for No TUP and Eq. (10) for TUP. These values can be used to define a distribution of loss-of-life percentage value.

4. Case study

4.1. *Case study description*

The loss-of-life of four step down PT (termed T1–T4) is assessed, technical characteristics are enlisted in Table 3; the operator began to store load and ambient temperature data on 20/01/2008, this study comprises the period from that date until 01/09/2016. Therefore, twenty-four values of both load and ambient temperature for each of the 3147 days listed in the database are available. Ambient temperature, load profile and the computed hot spot temperature for unit T1 are shown in Fig. 2.

Oil humidity measurements were performed simultaneously for all units; the water content is presented on Table 4. Fig. 3 shows 1000 profiles generated with the *BB* tool from January 2008 to May 2016. Considering the lack of information, the *ABM* is used from May to September 2016, because there is no water in oil content information but initial value, humidity evolution starts in the last known value; with $\sigma = 0.00709$ and $\mu = 0.0068$ computed from the average previous growing rates, this values are consistent with Ref. [40]; the red dotted line shows the mean value of all paths, this is a diffusive process for which uncertainty grows over time. Note that all paths in Fig. 3 passes through the known points.

To compare results, three alternatives to consider the influence of the chemical environment are proposed:

Alternative 1: proposed method ($A_{oxi} + A_{hyd} + A_{pyr}$), consists on assess paper degradation considering all degradation process and paper moisture dynamics.

Alternative 2: simplified proposed method (A_{hyd}), consist on to assess paper ageing considering both, thermal degradation and moisture variation but ignoring oxidation and pyrolysis. A_{hyd} values are taken from Eq. (7) or (8) depending on the paper class, final *DP* value is computed using Eq. (1) with A_{hyd} instead of *A*.

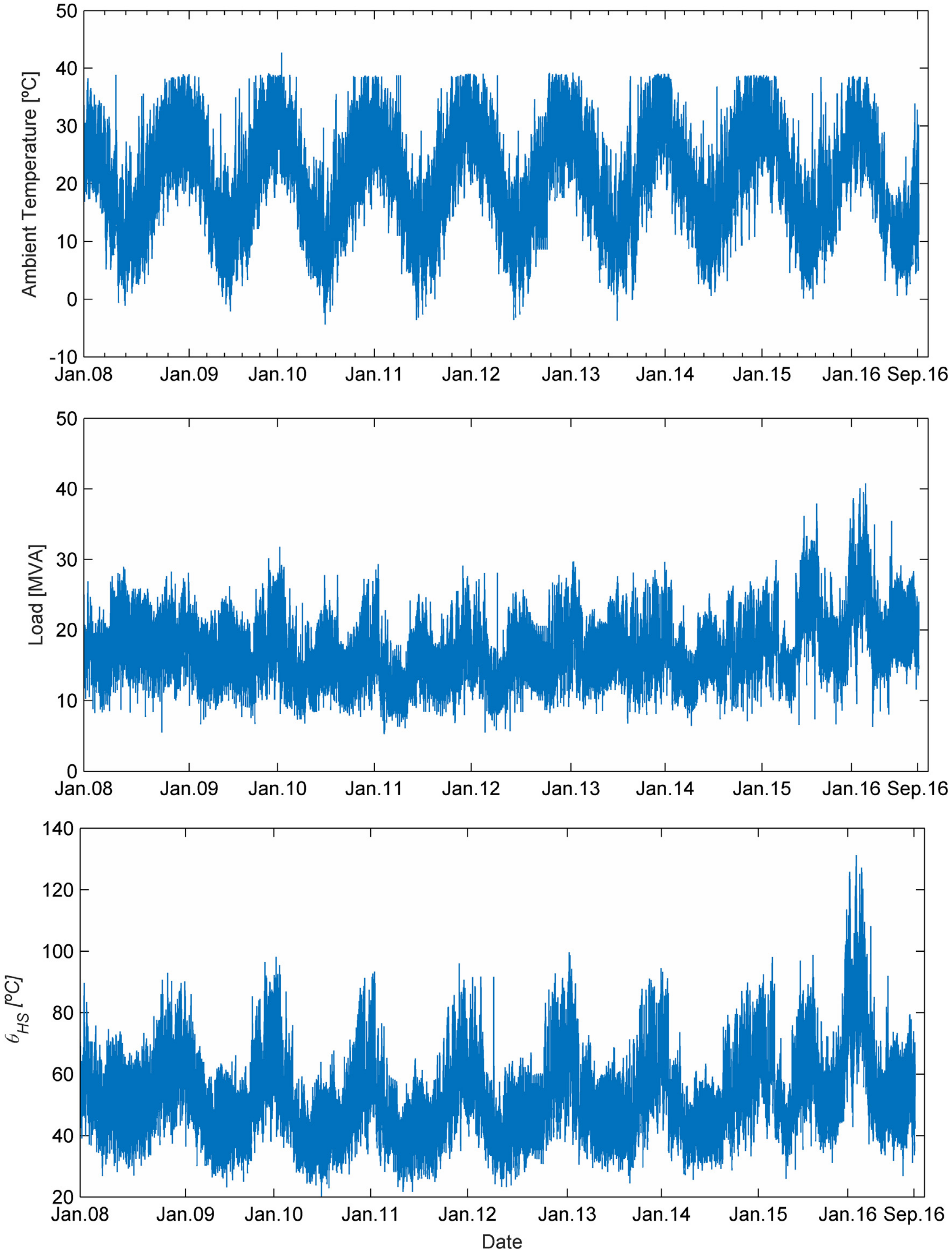


Fig. 2. Load, ambient temperature and θ_{HS} profiles for the period January 2008–September 2010.

Alternative 3: (A_{fix}) this alternative consist in to evaluate paper ageing by means of thermal degradation overlooking the influence of moisture variation; to this effect, pre-exponential factor, *A*, is assumed as a fixed value. The *A* value was proposed in Ref. [5] and corresponds to:

$$A_{fix} = \begin{cases} 3.62 \cdot 10^8 \rightarrow \text{No TUP} \\ 1.07 \cdot 10^7 \rightarrow \text{TUP} \end{cases} \tag{15}$$

Three previous presented alternatives uses the same θ_{HS} and H_p profiles computed with method proposed in Section 3.2.

Once the final *DP* is computed, loss-of-life calculations were performed by using Eq. (9) or (10), another degradation value was obtained from the IEEE C.57.91 approach [4].

Table 5 presents an overview of the main features of these three alternatives and IEEE C.57.91 proposal. It is important to remark that only T2 is insulated with thermally upgraded paper, the other units are insulated with regular paper.

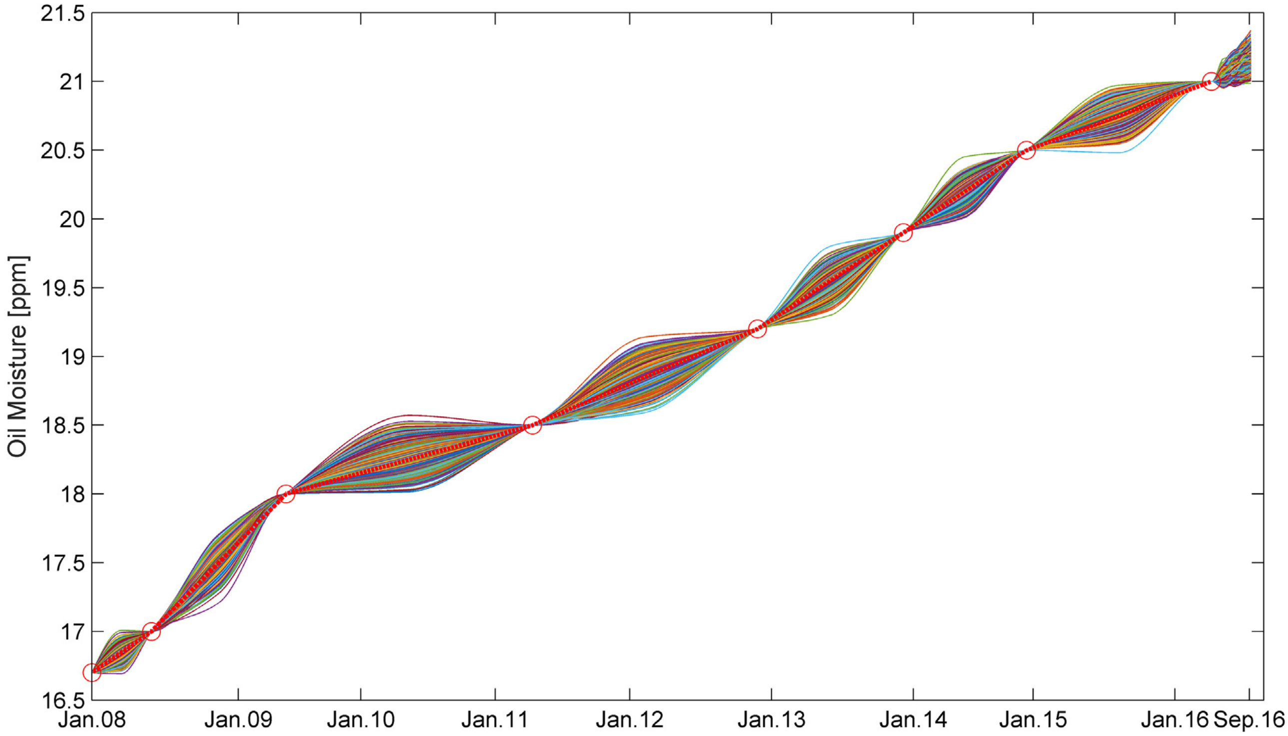


Fig. 3. Thousand random oil humidity profiles generated using BB and ABM.

Table 5
Main features of the compared loss-of-life methods.

Alternative	Paper moisture	$k(t)$		
Alternative 1 Proposed approach	Dynamic moisture	A_{oxi}	A_{hyd}	A_{pyr}
Alternative 2 Simplified proposed approach	Dynamic moisture	A_{hyd}		
Alternative 3	Not considered	A_{fix}		
IEEE C57.91 approach [4]	Not considered	Not considered		

There are no direct samples of paper taken from any unit then, initial *DP* value must be inferred from another source. Considering that, furan content analysis is a good alternative, the DP_0 was obtained from furan test applied over all units in January 2008. Proposed initial *DP* are: 684, 828, 625 and 688 for T1–T4 respectively.

It is noted that, when part of the data of load and ambient temperature profiles for the complete operational period of the transformer is missing, as it is just this case, available methods to estimate the unrecorded historical load data can be used [41]. However, such an estimation is out of the scope of this paper.

4.2. Results and discussion

For each unit, the *DP* values were computed according the previously outlined alternatives to consider the chemical environment. To this effect the same hot-spot-temperature profile was used, and in order to consider oil moisture uncertainty 1000 oil humidity profiles were proposed, Fig. 4 presents the 1000 computed H_p profiles for T1. Figs. 5–8 show assessed *DP* profiles for units T1–T4 respectively. There are a small dispersion in final *DP* values; this is because the only uncertain source is oil moisture.

It is remarkable that the θ_{HS} profile follows an annual cycle, with peaks every summer (from December to March), this situation produces an acceleration in the depolymerisation process.

For all units, the *DP* profiles assessed with Alternative 3, A_{fix}, presents the higher *DP* value than the other alternatives; this reflects that the omission of the influence of chemical environment inside the tank of PT trigger lower degradation rates. To ignore the influence of moisture lead the thermal degradation as the only ageing process in paper.

DP profiles assessed with Alternative 1, the proposed method, presents the lower value than the ones obtained with Alternative 2, simplified proposed method, although both alternatives considers moisture dynamic the simplified method ignores oxidative and pyrolytic degradation. Units operates under variable load cycles and in several periods, when units are uncharged oxidation is the main degradation process.

Table 6 summarizes the average final *DP* value and the variation in percentage of loss-of-life, at the beginning of the analysis period units have a value of percentage of loss of life, then in order to compare the variation in degradation the difference between initial and final loss of life is shown. The analysis was performed over 3147 days and it represents 75,528 h (around 50% of normal life—150,000 h). For all units alternative 3 presents the greater loss of life percentage.

5. Conclusions

This paper introduces a novel methodology to assess degradation of power transformer solid insulation considering thermal stress and moisture dynamics. A comparative study was conducted on four transformers for an 8.7 years period. The obtained results shows that the proposed method yields lower *DP* and loss-of-life values than alternatives that ignores oxidation and pyrolysis process.

It is wide accepted that state of the art methods:

- do not consider paper moisture variations properly,
- do not consider pyrolysis or oxidation,

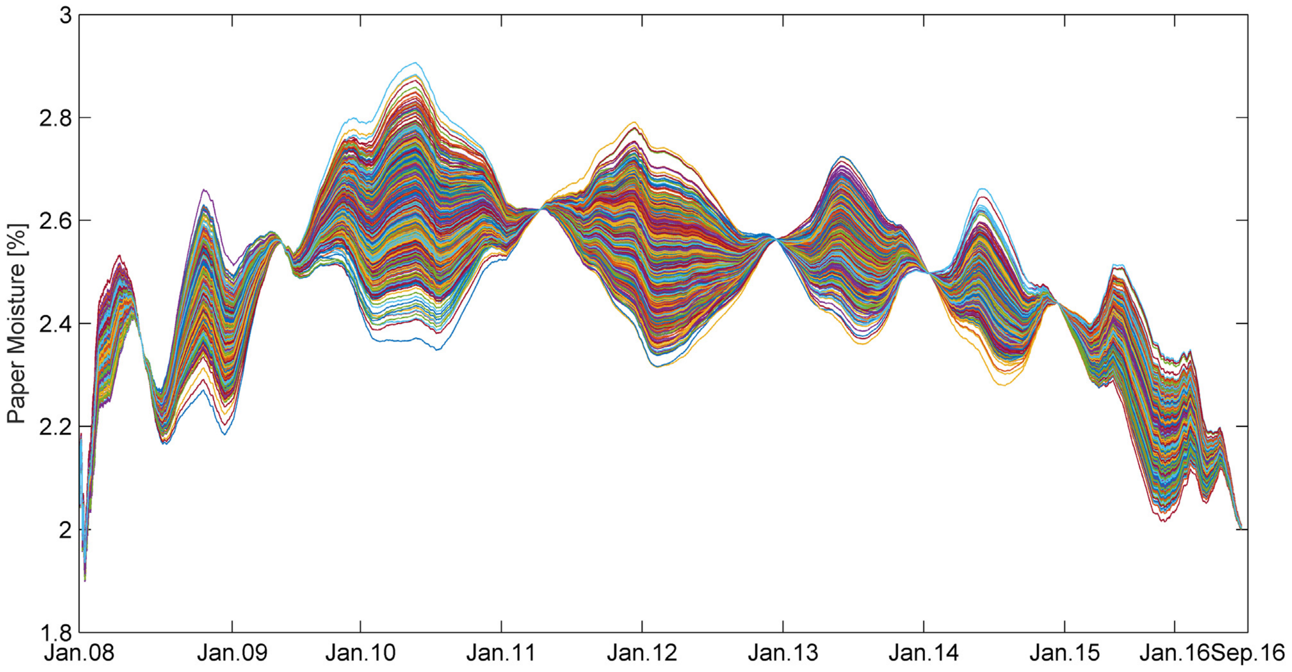


Fig. 4. Computed one thousand paper moisture profiles for T1.

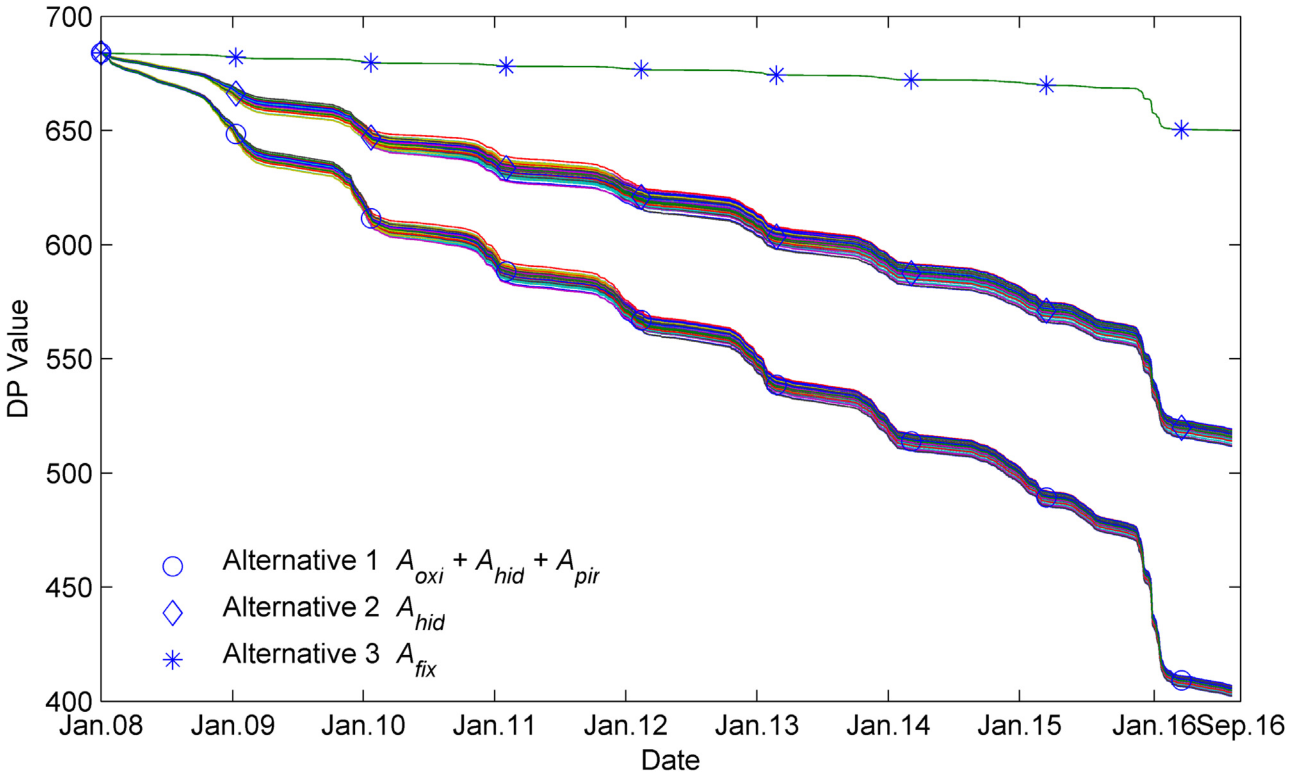


Fig. 5. *DP* profiles for unit T1 considering three proposed alternatives.

Table 6
Final *DP* and loss-of-life results.

	Average final DP				% loss-of-life			
	T1	T2	T3	T4	T1	T2	T3	T4
Alternative 1	405	562	407	399	49.08	27.93	48.73	50.16
Alternative 2	516	752	541	538	31.62	0	28.20	28.60
Alternative 3	650	790	595	650	14.96	0	21.34	14.96
IEEE C57.91	–	–	–	–	2.65	1.99	2.54	2.68

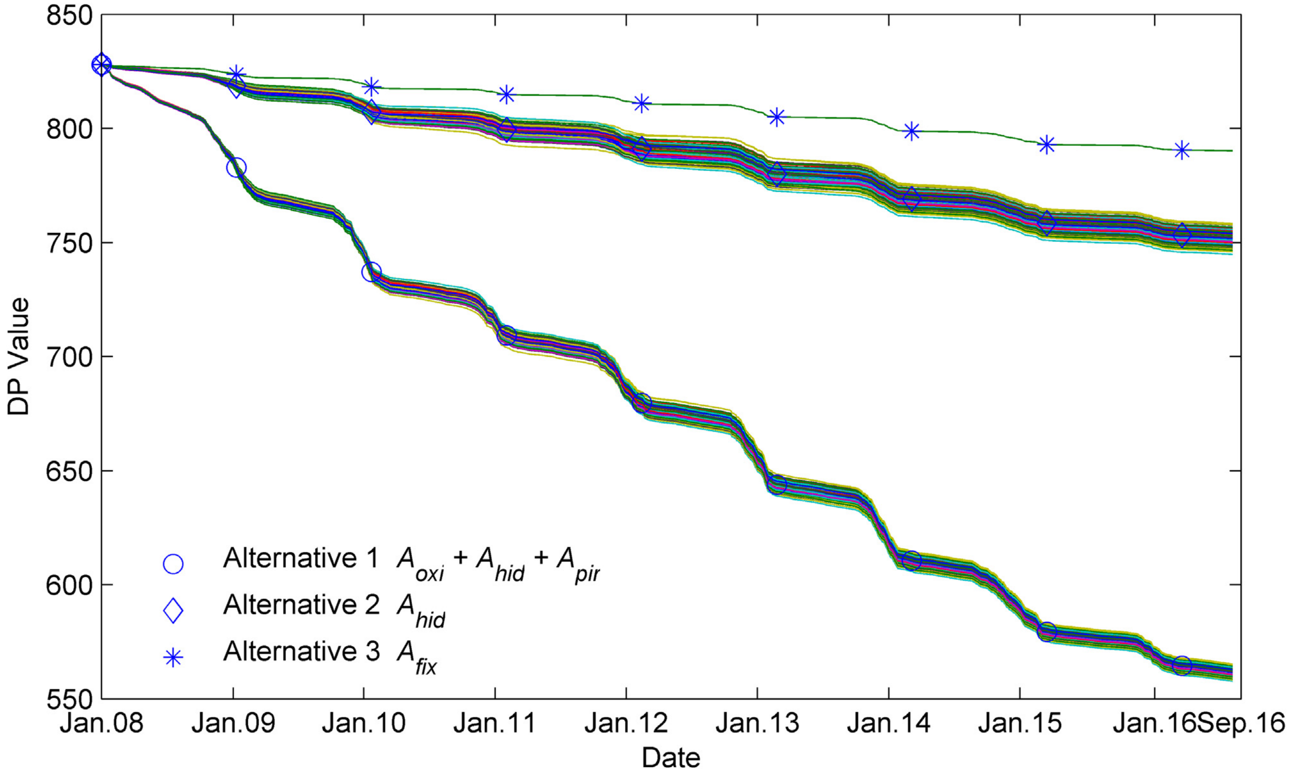


Fig. 6. *DP* profiles for unit T2 considering three proposed alternatives.

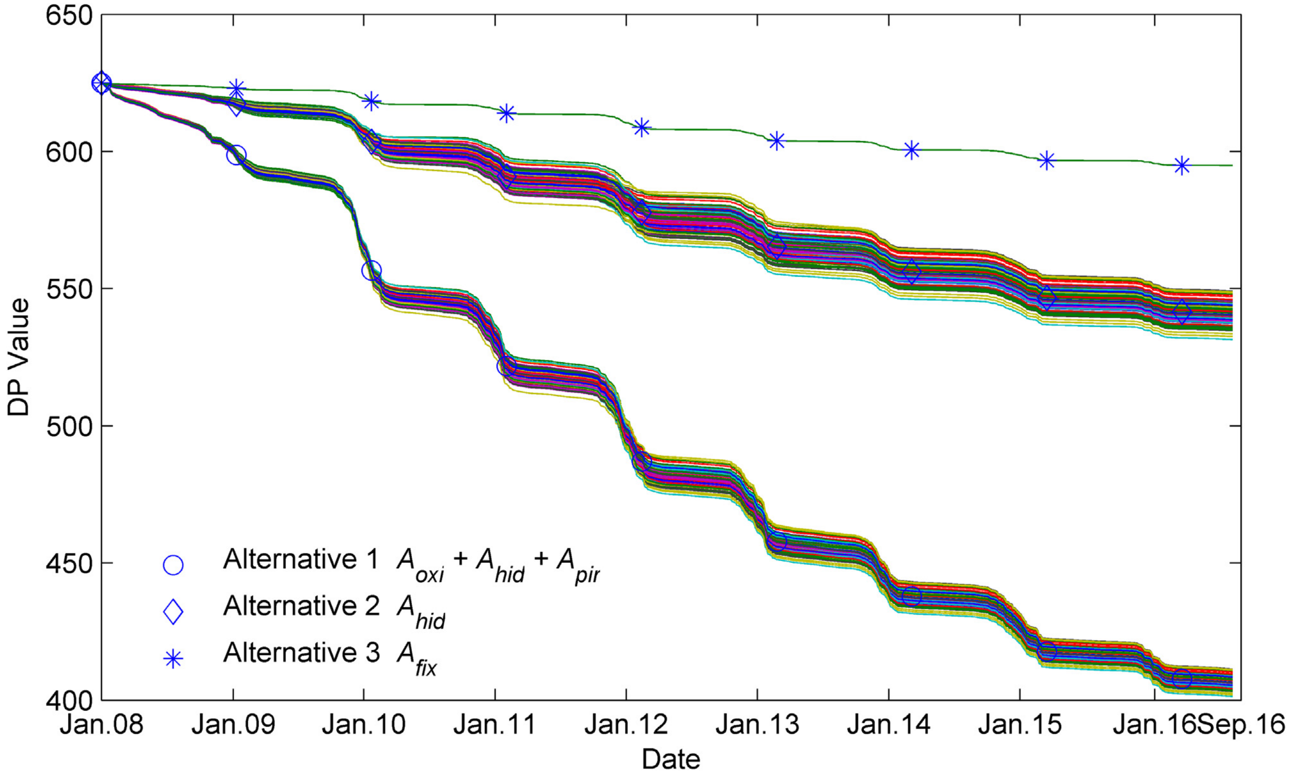


Fig. 7. *DP* profiles for unit T3 considering three proposed alternatives.

IEEE C57.91 considers thermal ageing ignoring paper moisture influence.

The proposed method introduces paper moisture dynamic and considers all paper-oil degradation processes; inclusion of new evidences lead more accurate degradation assessing e.g. when the transformer operates unloaded, the degradation is mainly produced by oxidation instead of hydrolysis and on the other hand, paper moisture increases due to low temperatures.

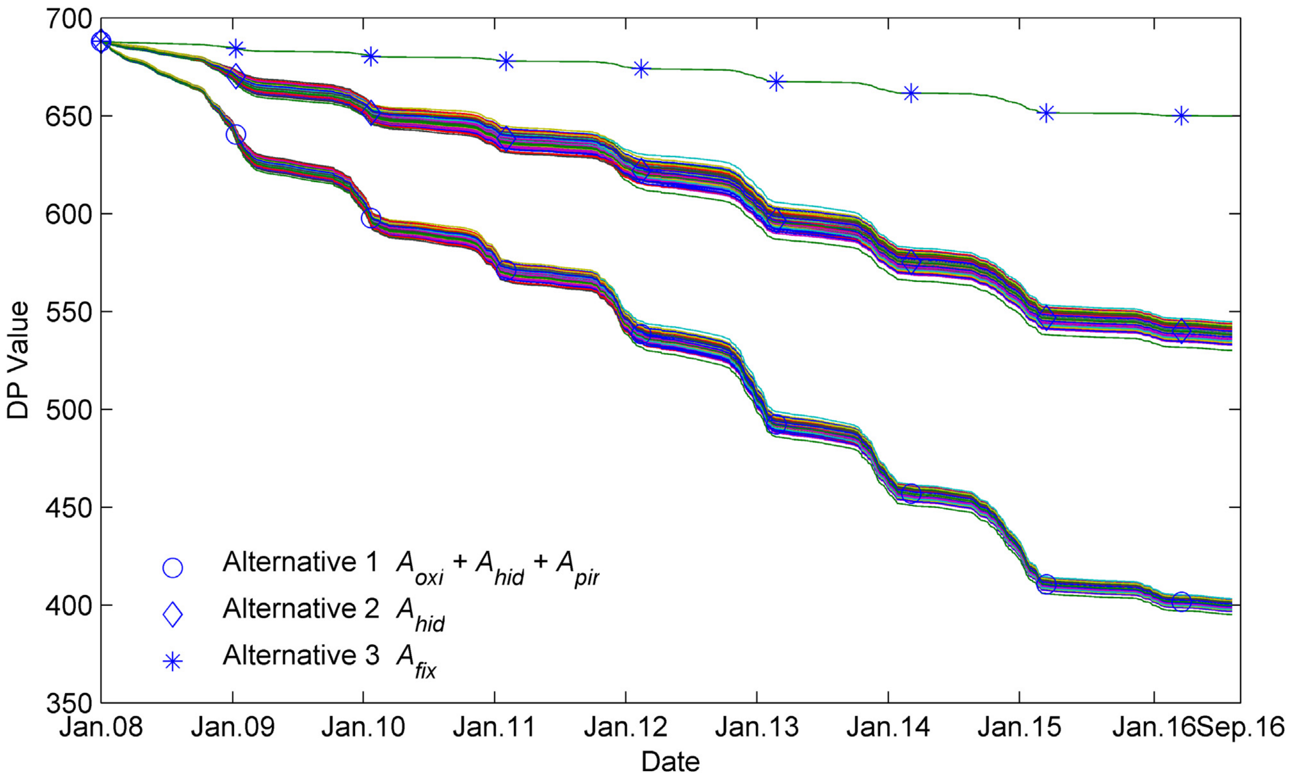


Fig. 8. *DP* profiles for unit T4 considering three proposed alternatives.

The main advantages of the proposed methodology are summarised as follows:

- Paper moisture can be roughly estimated considering operative conditions of the unit and test information.
- This work is supported by well-known methods and uses all evidences.
- This method can be widely used for NO-TUP and TUP.

Although the results presented have proven the effectiveness of this method, future work will be focused on: (i) analysis of the influence of different initial moisture values, (ii) generation of the complete historical profiles of load and ambient temperature from commissioning date to date using existent information to assess the present end-of-life value and, (iii) forecasting future load and ambient profiles in order to forecast end-of-life probable date.

Acknowledgements

This work was supported in part by DAAD, Grupo de Investigación en Energía – Universidad Politécnica Salesiana – Sede Cuenca and Agencia de Promoción Científica y Tecnológica (PICT 2012 - 0388).

References

[1] W. Bartley, An analysis of international transformer failures, part 1, Hartford Steam Boiler Inspection and Insurance Company, 2004.
[2] W. Flores, E. Mombello, G. Ratta, J.A. Jardini, Life of power transformers immerserd in oil. -State-of-the-art-part I. Correlation between life and temperature, IEEE Lat. Am. Trans. 5 (2007) 50–54.
[3] A. Abu-Siada, S. Islam, A new approach to identify power transformer criticality and asset management decision based on dissolved gas-in-oil analysis, IEEE Trans. Dielectr. Electr. Insul. 19 (2012) 1007–1012.
[4] IEEE, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators, IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995), 2012, pp. 1–123.
[5] A.M. Emsley, G.C. Stevens, Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers, IEEE Proc. Sci. Meas. Technol. 141 (1994) 324–334.
[6] N. Lelekakis, G. Wenyu, D. Martin, J. Wijaya, D. Susa, A field study of aging in paper-oil insulation systems, IEEE Electr. Insul. Mag. 28 (2012) 12–19.
[7] D.Y. Feng, Z.D. Wang, P. Jarman, Modeling thermal life expectancy of the UK transmission power transformers, ICHVE IEEE (2012) 540–543.
[8] A.E.B. Abu-Elanien, M.M.A. Salama, Asset management techniques for transformers, Electr. Power Syst. Res. 80 (2010) 456–464.
[9] J.L. Velasquez-Contreras, M.A. Sanz-Bobi, S. Galceran Arellano, General asset management model in the context of an electric utility: application to power transformers, Electr. Power Syst. Res. 81 (2011) 2015–2037.
[10] A.E.B. Abu-Elanien, M.M.A. Salama, A Monte Carlo approach for calculating the thermal lifetime of transformer insulation, Int. J. Electr. Power Energy Syst. 43 (2012) 481–487.
[11] D. Martin, Y. Cui, C. Ekanayake, H. Ma, T. Saha, An updated model to determine the life remaining of transformer insulation, IEEE Trans. Power Deliv. 30 (2015) 395–402.
[12] L.E. Lundgaard, W. Hansen, D. Linhjell, T.J. Painter, Aging of oil-impregnated paper in power transformers, IEEE Trans. Power Deliv. 19 (2004) 230–239.
[13] M.A.A. Wahab, M.M. Hamada, A. Mohamed, Artificial neural network and non-linear models for prediction of transformer oil residual operating time, Electr. Power Syst. Res. 81 (2011) 219–227.
[14] A.M. Emsley, The kinetics and mechanisms of degradation of cellulosic insulation in power transformers, Polym. Degrad. Stab. 44 (1994) 343–349.
[15] T.K. Saha, Review of modern diagnostic techniques for assessing insulation condition in aged transformers, IEEE Trans. Dielectr. Electr. Insul. 10 (2003) 903–917.
[16] Brochure Cigré, 323: Ageing of cellulose in mineral oil insulated transformers, Study Committee D 1 (2007).
[17] L.E. Lundgaard, W. Hansen, S. Ingebrigtsen, Ageing of mineral oil impregnated cellulose by acid catalysis, IEEE Trans. Dielectr. Electr. Insul. 15 (2008) 540–546.
[18] K.B. Liland, M. Kes, M.H.G. Ese, L.E. Lundgaard, B.E. Christensen, Study of oxidation and hydrolysis of oil impregnated paper insulation for transformers using a microcalorimeter, IEEE Trans. Dielectr. Electr. Insul. 18 (2011) 2059–2068.
[19] Brochure Cigre, 393, Thermal performance of transformers. Working Group A224 (2009).
[20] CIGRE, A227, Life Management Techniques for power transformers, CIGRE Work Group A2.18, 2003.
[21] D. Susa, Dynamic Thermal Modelling of Power Transformers, Department of Electrical and Communications Engineering, Helsinki University of Technology, 2005.

[22] R.D. Medina, A.A. Romero, E.E. Mombello, G. Ratta, Comparative study of two thermal aging estimating methods for power transformers, IEEE Lat. Am. Trans. 13 (2015) 3287–3293.

[23] T.K. Saha, P. Purkait, Understanding the impacts of moisture and thermal ageing on transformer's insulation by dielectric response and molecular weight measurements, IEEE Trans. Dielectr. Electr. Insul. 15 (2008) 568–582.

[24] J.P. Lata, R.D. Medina, W.P. Borja, D.X. Morales, Transformer common test description for condition management, 2016 IEEE International Conference on Automatica, ICA-ACCA 2016 (2016).

[25] Pahlavanpour, M. Martins, Eklund, Study of moisture equilibrium in oil-paper system with temperature variation, Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials, 2003 1123 (2003) 1124–1129.

[26] Y. Du, M. Zahn, B.C. Lesieutre, A.V. Mamishev, S.R. Lindgren, Moisture equilibrium in transformer paper-oil systems, IEEE Electr. Insul. Mag. 15 (1999) 11–20.

[27] W. Wei, W. Xin, M. Zhiqing, L. Chengrong, L. Shaoyu, W. Yanwei, H. Zhen, M. Jixian, L. Kaihua, Disequilibrium of moisture in oil-pressboard insulation under transient temperature condition, 2012 International Conference on Condition Monitoring and Diagnosis (CMD) (2012) 894–896.

[28] D. Martin, C. Perkasa, N. Lelekakis, Measuring paper water content of transformers: a new approach using cellulose isotherms in nonequilibrium conditions, IEEE Transactions on Power Delivery (2013) 1.

[29] M. Koch, S. Tenbohlen, T. Stirl, Diagnostic application of moisture equilibrium for power transformers, IEEE Trans. Power Deliv. 25 (2010) 2574–2581.

[30] D. Martin, T. Saha, M. Gibson, G. Buckley, S. Chinnarajan, R. Dee, G. Russell, T. Gray, K. Wyper, R. Li, K. Williams, Field studies on comparing techniques to measure the water content of power transformer insulation, 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC) (2015) 1–5.

[31] Y. Cui, H. Ma, T. Saha, C. Ekanayake, D. Martin, Moisture-dependent thermal modelling of power transformer, IEEE Trans. Power Deliv. 31 (2016) 2140–2150.

[32] N. Lelekakis, D. Martin, J. Wijaya, Ageing rate of paper insulation used in power transformers part 1: oil/paper system with low oxygen concentration, IEEE Trans. Dielectr. Electr. Insul. 19 (2012) 1999–2008.

[33] N. Lelekakis, D. Martin, J. Wijaya, Ageing rate of paper insulation used in power transformers part 2: oil/paper system with medium and high oxygen concentration, IEEE Trans. Dielectr. Electr. Insul. 19 (2012) 2009–2018.

[34] J.A. Conesa, J. Caballero, A. Marcilla, R. Font, Analysis of different kinetic models in the dynamic pyrolysis of cellulose, Thermochim. Acta 254 (1995) 175–192.

[35] R. Capart, L. Khezami, A.K. Burnham, Assessment of various kinetic models for the pyrolysis of a microgranular cellulose, Thermochim. Acta 417 (2004) 79–89.

[36] T. Kashiwagi, H. Nambu, Global kinetic constants for thermal oxidative degradation of a cellulosic paper, Combust. Flame 88 (1992) 345–368.

[37] R.D. Stebbins, D.S. Myers, A.B. Shkolnik, Furanic compounds in dielectric liquid samples: review and update of diagnostic interpretation and estimation of insulation ageing, Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials, 2003 923 (2003) 921–926.

[38] P.K. Sen, P. Sarunpong, Overloading and loss-of-life assessment guidelines of oil-cooled transformers, Rural Electric Power Conference, 2001 (2001), pp. B4/1–B4/8.

[39] I. Karatzas, S. Shreve, Brownian Motion and Stochastic Calculus, Springer Science & Business Media, 2012.

[40] P. Griffin, V. Sokolv, B. Vanin, Moisture equilibrium and moisture migration within transformer insulation systems, CIGRE Working Group A2 30 3 (2008).

[41] A.A. Romero-Quete, E.E. Mombello, G. Rattá, Assessing the loss-of-insulation life of power transformers by estimating their historical loads and ambient temperature profiles using ANNs and Monte Carlo simulations, Dyna 83 (2016) 104–113.