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

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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

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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:

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

with:

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

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