CHEMICAL INDICATORS AND AGEING DIAGNOSIS OF MV / LV DISTRIBUTION TRANSFORMERS

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ABSTRACT

This article presents the investigations carried out on the MV/LV transformers for the use of methanol (MeOH) and furfuraldehyde (2-FAL) as indicators of the transformer ageing state under operating conditions. In parallel, an accelerated ageing experiment of paper-oil system in sealed vials confirmed the production of MeOH and 2-FAL and showed the relation between their concentrations in oil and the degree of polymerization (DPv) of the paper.

INTRODUCTION

The need for estimation of the ageing state of MV/LV distribution transformers is an important issue for managers and operators of the electrical network. The solid insulation (cellulose materials impregnated with mineral oil) being the most fragile component of these devices, the objective of this study is thus to find a simple and robust assessment of the degradation of paper.
Accelerated thermal ageing experiments of combinations of mineral insulating oils and papers have highlighted the formation of furanic compounds, mainly 2-FAL, and of MeOH during the ageing [1, 2]. This article presents the work carried out in the laboratory, as well as the expertise on transformers, in order to verify the usefulness of such indicators in real operating conditions.

ACCELERED THERMAL AGEING EXPERIMENT IN LABORATORY

Test setup

This accelerated ageing test was carried out in glass sealed vials after the conditioning of the samples of oil and paper. The main purpose was here to analyze the evolution of the ageing with different initial conditions (water content, DPv etc.).
We carried out two series of experiments in which the initial water content of the paper was set at less than 0.5% and about 1% in order to observe the ageing behavior of wet and dry papers.

Other test parameters were set as follows:

Container: Glass vials of 200 mL (Figure 1). Vials, after the introduction of oil and paper samples (with wrapped copper), are filled with argon and hermetically sealed.

Oil: Unused uninhibited insulating mineral oil, 100 mL/vial.

Paper (+ copper): Sections of flat naked copper conductor, wrapped with Kraft paper (4 layers) (see detailed description in IEC 62535 § 5.2).

Ageing conditions: After flame sealing (Figure 1), the vials containing the samples are placed in three ovens thermally stabilized at 98°C, 110°C and 122°C.

Figure 1. Sample sealing and samples' initial composition

Test results

The main results of this test are presented in Figure 2 and Figure 3.

The Figure 2 shows that the more the paper is wet ([H_2O] ≈ 1%), the more important the degradation is. Similarly, Figure 3 shows that the production of 2-FAL and MeOH is greater when the paper is wetter. Moreover the 2 figures show the influence of the temperature on the speed and intensity of the phenomena.
At both temperatures, MeOH appears in higher concentration than 2-FAL in the early days of ageing. These results are in accordance with those of [1] showing that the production of MeOH is proportional to the number of splits in the cellulose chain of the paper. So, at 122 °C the concentration of 2-FAL remains less than 0.5 ppm throughout the test (3 months), while MeOH concentration exceeds 1 ppm after only one month.
In addition, it has been observed that 2-FAL still does not reach the detection threshold of the analytical method after 2 months of ageing at 98°C (and 15 days at 122 °C), while methanol is detectable after 10 days at 9**8** °C (and 4 days at 122 °C).
Meanwhile, at 98 °C the DPv is almost unchanged, even if a downward trend is observed over a period of two months. This trend is corroborated by the appearance of MeOH but remains invisible from measurements of 2-FAL.
These observations confirm that methanol is a marker that appears early in the ageing of cellulose.

Figure 4, curve 2-FAL in function of DPv, shows a clear exponential relationship between these two variables (confirmed by the bibliography), while the curve MeOH vs. DPv highlights a relationship rather linear (in agreement with the results of [1]).
MeOH production appears to be proportional to the number of ruptures occurring in the cellulose chains, justifying the fact that it can be detected from the earliest state of paper's ageing (DPv > 900).
In contrast, the production of 2-FAL is very low or undetectable in early ageing of cellulosic materials, i.e. until a DPv around 600. Subsequently, the 2-FAL concentration increases quickly (exponentially) and reaches levels that finally exceeds those of MeOH.
According to the results published by IREQ, MeOH evolution can be modeled by two linear domains:
- The first one (DPv > 700): with a steep slope. It corresponds to the degradation of the region in which the cellulose molecules are disordered (amorphous domains)
- The second one is associated with the attack of cellulose molecules in areas where their assembly is better organized (in the form of pseudo-crystals), i.e. less accessible so the depolymerization is slower (lower slope).

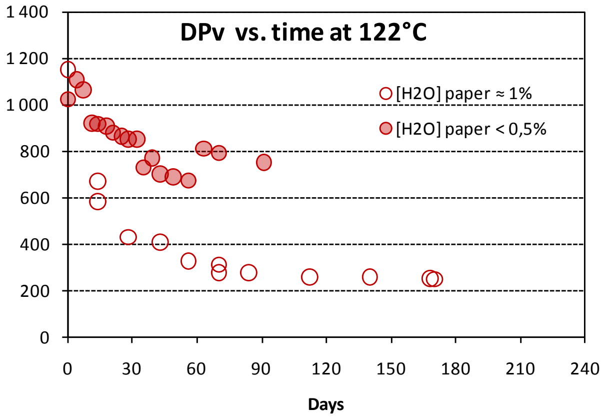

Figure 2. Evolution of DPv at 122 °C with 2 initial levels of water contents in paper

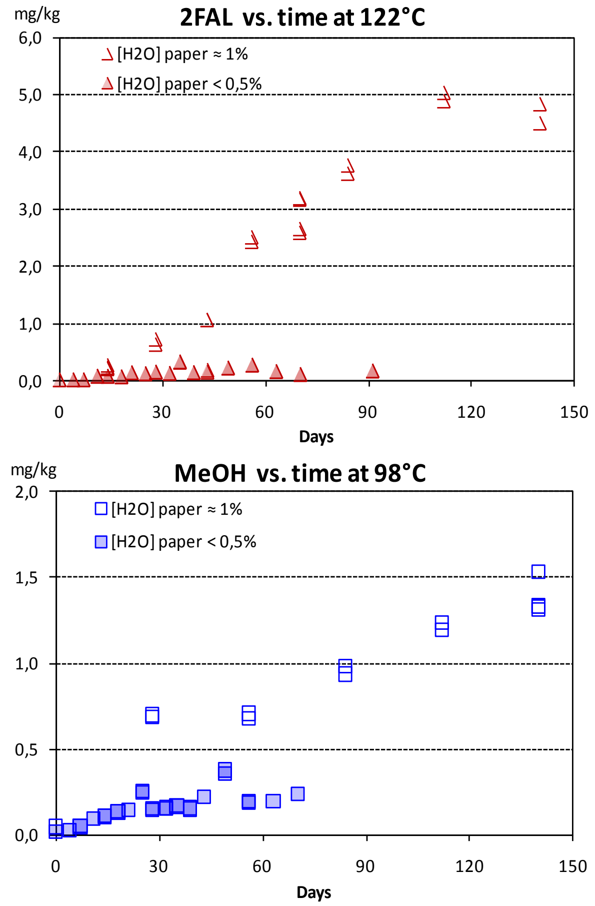

Figure 3. Evolution of the 2-FAL at 122 °C and MeOH at 98 °C (in ppm) with different initial levels of water content in the paper

Our results partly confirm this model because we observe for DPv between 1000 and 700, a first region where the experimental points seem well aligned. For DPv < 700, the points are much more dispersed.
The results obtained in laboratory conditions showed the existence of a one-to-one relationship between the concentrations in oil of MeOH or 2-FAL and paper ageing

assessed by DPv. The observed kinetics are not inconsistence with the results reported by the scientific community.

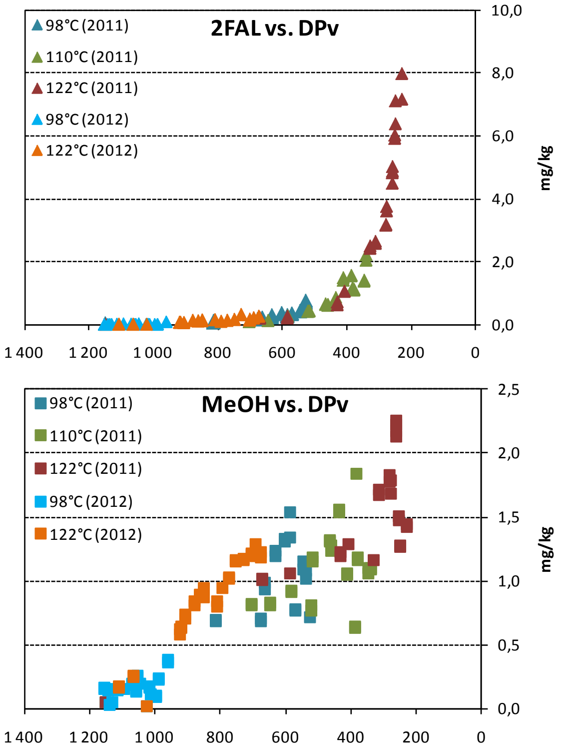

Figure 4. 2-FAL and MeOH concentrations versus DPv, at different temperature and moisture levels (2011 i.e. 1% and 2012 i.e. < 0.5%).

Therefore, to ensure that the use of these chemical indicators can be applicable to the diagnosis of the ageing of MV/LV distribution transformers, we have investigated in 33 transformers from the network. The next chapter presents the works carried out on these actual cases.

EXPERTISE ON MV/LV DISTRIBUTION TRANSFORMERS

Presentation of transformers

The studied MV/LV distribution transformers were put in operation between 1958 and 1987. These transformers are rated between 25 and 400 kVA and operate at 15 or 20 kV / 400 V (lowly loaded). All are sealed type (no contact with the ambient air) and filled with uninhibited mineral oil.

Oil was sampled on 33 transformers and 15 of these have been off tank allowing paper collection. Among these 33 devices, 3 have been recently refilled (the 30 others still contained their original oil).

During these assessments, the MeOH and 2-FAL contents in oil and DPvs on several cellulosic materials (wrapping, paper, pressboard) coming from different places in transformers were measured, as well as oil acidity in order to evaluate the oil degradation.

Figure 5. Off tank of transformers and sampling.

Observations on MeOH and 2-FAL concentrations

MeOH was analyzed in 28 transformers and the results show that MeOH is detectable in 26 of them. This confirms a noticeable production of MeOH during the transformer ageing in real conditions (concentrations range between 0.03 and 2.7 ppm). In contrast, 2-FAL is detectable in only 8 of 33 analyzed oil samples.

Note that three transformers refilled shortly before the off-tank contain also detectable amounts of MeOH; moreover, despite its volatility, MeOH remains detectable in samples taken several years ago (2-5 years before analysis) and stored without specific precautions.

The viscometric degrees of polymerization (DPv) are measured on various cellulosic samples. Considering that chemical indicators correspond to the overall depolymerization of cellulose due to the transformer ageing, their concentration could be correlated to an average DPv. So we calculated the average DPv from the 2 to 7 sample available by transformer, and results range between 423 and 1170.

However, knowing that the end of life is ultimately depends on the most degraded area (hot spot); we also focus on the minimum values of DPv. The measured DPv min is ranged between 282 and 1080.

The Figure 6 and Figure 7 show the distribution of MeOH and 2-FAL contents in the transformer according to the age in operation.

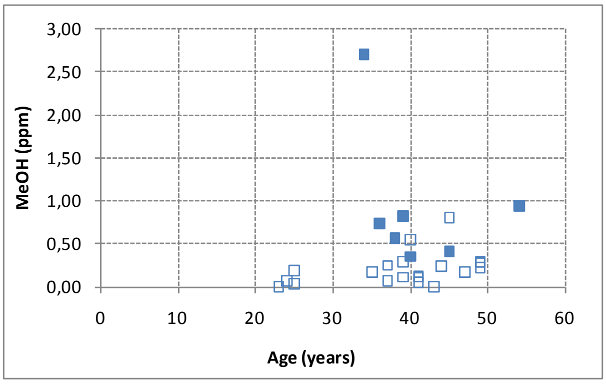

Figure 6. MeOH concentration in transformers versus age.

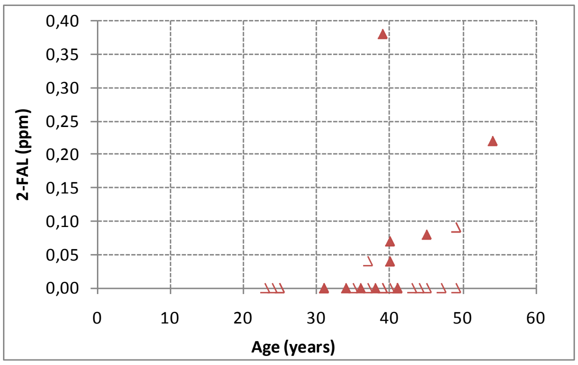

Figure 7. 2-FAL concentration in transformers versus age.

MeOH content tends to increase with age on the Figure 6, which is consistent with the behavior observed during laboratory tests of accelerated ageing.
On Figure 7, the 2-FAL is only detectable in 7 samples corresponding to transformers older than 37 years and among those for which the MeOH content is high ($\geq$ 0.3 ppm). 5 transformers over these 7 have very low DPv values, less than 640.
These data confirm the existence of a connection between the transformer ageing and the degradation of cellulosic materials as seen through the concentrations of chemical markers.
We can also note that this approach allows the screening of atypical transformers i.e. devices where the measurements are very different from those of the rest of the tested population. Such transformers are thus supposed to have a premature ageing and could be subjected to further investigations.
In agreement with the laboratory tests, we observed the MeOH appears in oil as soon as a transformer begins to age, while the 2-FAL is detectable only after a significant ageing of the paper. Further, our investigations demonstrate physico-chemical stabilities of the markers rather favorable to our purpose: the degradation and/or evaporation of 2-FAL and MeOH in oil samples are moderate enough to ensure easy samples representative of the transformer state.

CONCLUSIONS

Our laboratory experiments showed a correlation between the concentrations of MeOH and 2 FAL measured in oil and the evolution of paper DPv. They also confirm previous observations of the scientific community: MeOH is produced from the very first breaks in the cellulose chain, while the 2-FAL, as a sub-product of the chain reactions involved in the degradation of the cellulose, is detectable in the oil after the paper has undergone a further degradation (in duration and/or intensity).
The investigations carried out on MV/LV distribution transformers showed the following specific properties:

- The indicators are stable enough in oil samples to ensure a satisfactory reliability of their concentration measurements (detection and quantification) in terms of transformer ageing that is favorable to our ultimate goal.

- The MeOH is abundant enough to be easily quantified in MV/LV distribution transformers. However, in our investigations, among transformers of the same age, MeOH concentrations are relatively dispersed. At this stage of study, and because of the lack of sufficient feedback, the use of MeOH content cannot yet conclude with adequate confidence on the paper degradation and transformer ageing. But, in the near future, we should be able to define a threshold for unacceptable ageing.

- Though 2-FAL is less volatile than MeOH, its concentration in MV/LV transformers is, in most cases, undetectable or very low, even after several decades of ageing (corresponding to significant damage). So the use of 2-FAL as a marker to assess the early ageing of transformers is not established.

Nevertheless, this work confirms the relevance of the use of chemical markers of cellulose degradation, namely methanol (MeOH) and 2-furfuraldehyde (2-FAL), for the diagnosis of the ageing state of MV/LV distribution transformers in service. Moreover, our first results indicate that the concentration of methanol in transformer oil is a promising screening criterion.

REFERENCE

[1] J. Jalbert et al, “Kinetic of the production of chain-end groups and methanol from the depolymerization of cellulose during the ageing of paper/oil system. Part 1: Standard wood Kraft insulation”, Cellulose (2009) vol 16, p 327-338

[2] A. Emsley et al, “Degradation of cellulosic insulation in power transformer, Part 2 : Formation of furan products in insulating oil”, IEE Proc.-Sci. Meas. Technol., vol. 147, No.3, May 2000.