This is a postprint version of the following published document:


DOI: [https://doi.org/10.1016/j.epsr.2016.06.036](https://doi.org/10.1016/j.epsr.2016.06.036)

© 2016 Elsevier B.V. All rights reserved.

This work is licensed under a Creative Commons AttributionNonCommercialNoDerivatives 4.0 International License
Investigating the influence of moisture on the 2FAL generation rate of transformers: a new model to estimate the DP of cellulosic insulation.

B. García¹, D. Urquiza², J. C. Burgos¹

¹Universidad Carlos III de Madrid, Department of Electrical Engineering, C/ Butarque 15, 28911 Leganés, Madrid, Spain

²Cr. Villaviciosa de Odón a Móstoles (M-856) Km 1.5, 28935 Móstoles, Madrid, Spain.

ABSTRACT

The analysis of the concentration of furanic compounds in oil has been accepted as one of the most reliable methods to obtain information about the condition of the transformer’s cellulosic insulation. Although this technique has been used for years, the interpretation of the analysis results is still a challenge. Several authors have agreed that factors such as the acidity of the oil and the moisture content of the solid insulation have an influence on the furanic compound generation rate.

In this paper, the relation between the moisture content of the paper and the rate of generation of 2-furfuraldehyde (2FAL) is studied. A statistical study is carried out to determine if transformers with higher moisture contents in oil tend to present higher contents of 2FAL, and, to this end, a database with more than 20,000 historical records of transformers is utilized. This study is completed with a set of accelerated ageing tests of transformer cellulosic insulation pieces, conditioned with different moisture contents. The impact of the moisture content of paper on the relation between the degree of polymerization (DP) and the 2FAL concentration is determined, and a correction factor has been proposed to include this variable in a model that relates 2FAL in oil and the DP of paper.
KEY WORDS
Transformer solid insulation ageing, furanic compounds, 2FAL, diagnostic model, moisture-in-paper, accelerated ageing tests, mineral oil, degree of polymerization.

1 INTRODUCTION

The ability to estimate the remaining life of a transformer is important for optimizing its loading capacity and implementing adequate maintenance and replacement programmes. The actual age of a transformer is linked to the condition of its solid insulation, which is mainly composed of Kraft paper and pressboard.

Although transformer design-life is considered to be approximately 30 years, experience shows that a number of transformers are still in suitable condition after 50 years of service [1,2]. The ageing rate of cellulosic insulation mainly depends on the transformer’s operating temperature, but it is also influenced by the presence of certain harmful agents, such as moisture, oxygen and acids [3]. The levels of these factors are linked to the operating conditions and the maintenance practices applied to the transformers during their lives, and in many cases, no registers of their historical values are available.

Determining the remaining life of transformer insulation is not an easy task. Cost and safety concerns make it unfeasible to extract paper samples from the active part of the transformer to carry out direct determinations of their condition. In consequence, estimations of transformer life should always be obtained from indirect calculations involving a large number of uncertainties.

Cellulose degradation in transformers proceeds via a complex sequence of chemical reactions. The ageing process involves the cleavage of polymer chains and the release of products such as hydrogen, short-chain hydrocarbons, carbon monoxide, carbon dioxide, furanic compounds and water. A portion of those products remains dissolved in the transformer oil, and thus the measure of their concentrations (obtained through an analysis of dissolved gas) can be used to obtain information about the condition of the transformer’s solid insulation.
The furanic compounds are among the most widely used markers to assess the condition of the paper [4]. The advantage of furanes over other markers is that they are solely related to the degradation of solid insulation. Although six types of furanic compounds can be found in transformer oil (5Hydroxymethyl-2Furfural-5HMF, 2Furfuraldehyde-2FAL, 2Acetylfuran-2ACF, 5Metyl-2Furfural-5MEF, and 2Furoic Acid), most of the reported studies are focused on the analysis of 2FAL, which is found in much higher concentrations.

Different authors have found relations between the furanic compound concentrations measured in oil and the condition of the cellulosic insulation of a transformer [3]. As the degree of polymerization (DP) has been accepted as a reliable indicator of the condition of the Kraft paper, different models have been proposed to relate the DP of paper with the concentration of furanes in oil [5-,13].

Two of the most widely accepted models are those developed by Chengdong [5] and by De Pablo [6], shown in equations (1) and (2), respectively.

\[
\log_{10}(2\text{FAL}_{ppm}) = 1,51 - 0,0035 \times DP \\
\]

\[
DP = \frac{809}{0.186 \cdot 2\text{FAL}_{ppm} + 1} \\
\]

Various other models are based on logarithmic relations, such as the model proposed by Burton [7] or that proposed by Vuarchex [8] (equations (3) and (4)).

\[
\log_{10}(2\text{FAL}_{ppm}) = 2,5 - 0,005 \times DP \\
\]

\[
\log_{10}(2\text{FAL}_{ppm}) = 2,6 - 0,0049 \times DP \\
\]
In recent years, other authors have proposed models based on the total concentration of furan (TOT_F) (5), valid in the case of thermally upgraded paper, or taking into account the concentration of CO and CO₂ in oil (6) [9,10].

\[ DP = 356.1 - 343.8 \cdot \log_{10}(TOT_F) \quad (5) \]

\[ DP = C_0 + a \cdot \log(CO) + b \cdot \log(CO_2) + c \cdot \log(TOT_F) + d \cdot \log(2FAL) + e \cdot \log(2ACF) + f \cdot \log(5MEF - 2FAL) \quad (6) \]

where a to f are parameters and CO, CO₂, TOT_F, 2FAL, 2ACF, 5MEF and 2FAL are expressed in ppm.

In [14], Feng presents a literature review of the DP vs. 2FAL models that have been proposed by different authors, including a comparative study of the models.

Cigré Working Group D1.01 (TF13) has recently published a report on the Furanic-compounds-based diagnosis of transformers [3]. The report includes a description of the different factors that influence the generation rate of those markers during the operation of a transformer, which are the temperature, closely related to the ageing rate of the solid insulation, the moisture content of the insulation, and the condition and type of oil in the transformer.

Cigré also claims that, although establishing relations, such as those previously described, between DP and furanic compound concentration is important for interpreting the results of analysis, other factors, such as moisture or acids, have a non-negligible effect on the 2FAL formation kinetics.

Several authors have studied the influence of the moisture content of the insulation on the generation of 2FAL [3, 15-17]. Researchers from a transformer manufacturer company found clear evidence of the relation between 2FAL concentration and moisture, and as a final remark in [18], they claim that “further work is necessary to combine these important aging characteristics into a valuable tool for the assessment of a large aging transformer population.”
In this paper, a study devoted to gaining insight into the influence of the moisture content of the insulation on the 2FAL generation rate is presented. The relation between 2FAL and moisture content of paper (MP) was studied in real transformers following a statistical approach. To this end, a database containing more than 20,000 records of field transformer oil analysis was studied, finding typical 2FAL concentrations and their relation to the moisture content of oil.

Afterwards, laboratory analysis was conducted on samples of paper that were conditioned with different moisture levels and subjected to an accelerated ageing process. The evolution of 2FAL and DP was monitored throughout the ageing tests, and a relation was found between these three variables. The proposed relation was validated using experimental data and compared with other authors’ equations, finding that, by considering the water content of solid insulation, it is possible to obtain a more accurate estimation of the remaining life of the equipment.

2. RELATION BETWEEN 2FAL AND MOISTURE IN OIL FOR IN-SERVICE TRANSFORMERS

The relation between the moisture content of oil and the concentration of 2FAL of in-service-transformers has been investigated using a database of 20,000 records generated by the company CEIS during the years 1993 to 2013. The database includes oil analysis performed on 8,275 transformers, mainly of the free-breathing type, from more than 100 different companies involved in the generation, transmission and distribution of electrical power, industries and transformer manufacturers.

The transformers of the database were split into populations according to their oil moisture contents, considering moisture levels from 0 to 60 ppm. The average 2FAL concentration of the transformers included in each category was calculated and plotted in Figure 1. As shown in this figure, a very clear correlation appears between both variables.
To investigate if that relation is linked to the fact that older transformers have higher moisture contents, the database was once more divided into populations. The records were classified according to the number of years in service of the transformer. The average moisture contents of the transformers in the different age groups are shown in Figure 2a. As shown in this figure, the newest transformers tend to have lower moisture contents. However, after some years in operation, the moisture content tends to stabilize, and it does not seem to further increase with the age of the transformer. The decrease in moisture of older transformers is perhaps related to field drying operations. The fact that a transformer presents a certain moisture content is more related to the maintenance activities applied to the equipment during its life than to its age. The high moisture contents found in certain transformers may be due to various events, such as accidental contamination during field repairs, leakage problems or water ingress through the conservation system.

A similar curve was obtained to show the average 2FAL concentration in oil for the different age groups (Figure 2b). As expected, the 2FAL concentration tends to grow with age. It can be noticed that, in transformers age group of 35-45, the average content of 2FAL does not grow significantly, which seems to be related to the decrease in average moisture for transformers of this age group. In the last range of ages (45-60 years in service), the average 2FAL concentration grows sharply, most likely because of the effect...
of polymer chain cleavage, which is related to the 2FAL generation rate by an exponential relation that prevails over the effect of moisture.

![Figure 2](image)

**Figure 2.** Average water content (a) and 2FAL (b) in oil for transformers in different age groups.

Calculated from the CEIS database.

Finally, the database was split into categories according to the concentration of 2FAL measured in the transformer oil. The 0, 50, 90, 95 and 98 percentiles of 2FAL were calculated, and the average moistures of oil (MO) of the transformers within each of these percentiles were calculated and are shown in Figure 3 for each age group. As shown in this figure, the average MO has a clear increase as we move to populations with higher concentrations of 2FAL, while the average MO does not increase with age, except for transformers with less than 15 years of service.
**Figure 3.** Relation between the moisture content of oil and the age of the transformer. Study for different values of 2FAL.

The same fact can be observed in Figure 4, where the relation between the 2FAL concentration and the MO is once more shown for all the transformers in the database and for different age-population groups.

**Figure 4.** Average water content in oil of the different 2FAL percentiles for different populations.

All of the previous analysis seems to indicate that the concentration of 2FAL is somehow related to the moisture content in oil. This relation could be due to an acceleration of the 2FAL generation rate for wet transformers or because of a change in the ratios of distribution between paper and oil, as some authors have suggested. Taking into account the evolution of the average moisture and 2FAL concentration in oil...
of the different age-groups, it seems clear that this effect is not because older transformers are generally more wet.

Not taking into account the relation between 2FAL generation and the moisture content of transformer insulation could lead to a misinterpretation of the content of 2FAL in humid transformers, and the estimated DPs could be lower than the actual ones.

The information that can be extracted from a statistical study, such as the previous one, is certainly limited, as some important information related to the management of the transformers (load, maintenance, oil treatments, etc.) is not available in the database. However, given the great number of data points included in the study, the conclusions are certainly representative of what occurs in field transformers.

To study the relation between ageing and 2FAL concentration in detail, a deeper study has been conducted in the laboratory under controlled conditions, as described in the following sections.

3. EXPERIMENTAL STUDY

An experimental study was performed to analyse the influence of moisture on the 2FAL generation rate during the ageing process of paper.

Ageing tests were conducted in vials containing oil, cooper and paper with different moisture contents, as will be explained next. The properties of the paper and oil used in this work are shown in Table 1.

| Table 1. Properties the mineral oil and the paper used in the experimental study |
|---------------------------------|-----------------|
| **OIL PROPERTIES**             |                 |
| Viscosity at 40ºC              | 10 mm²/s        |
| Density at 20ºC                | 0.870 kg/dm³    |
| Flash point min limit          | 152 ºC          |
| Pour point max limit           | 48 ºC           |
The Kraft paper used in the study was extracted from a paper-insulated copper conductor wire. The paper insulation of the wire was unwrapped and placed in glass vials for the accelerated ageing process (Fig. 5).

**Figure 5.** Specimens of Kraft paper for the ageing process.

Aiming to reproduce the ageing conditions of paper in a real transformer, a piece of paper-insulated copper conductor was also introduced to the vials. The amounts of paper, oil and cooper introduced in each vial are shown in Table 2

**Table 2.** Proportions of the different materials used in the ageing tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>12 strips</td>
<td>2,9832</td>
</tr>
<tr>
<td>Oil</td>
<td>100 ml</td>
<td>87</td>
</tr>
<tr>
<td>Cooper</td>
<td>1 conductor</td>
<td>8</td>
</tr>
</tbody>
</table>
The preparation of the test specimens involved an initial drying process performed at 70 °C and 1 mbar to avoid accelerated aging of the paper. Different drying times were applied to obtain samples with different initial moisture levels.

A previous study was conducted to determine the drying times. The measurements were carried out on paper samples kept in the oven for different periods of time to find the drying times required to obtain the desired moisture contents under the applied temperature and vacuum. Additionally, the homogeneity of the total amount of paper inside each vial was analysed, yielding adequate results. In all cases, the determination of the moisture content of the paper sample was performed via Karl Fischer titration according to the IEC-60814 standard.

Moreover, the vials used to test every particular condition of temperature and moisture content were prepared in the same drying process, i.e., all the vials where dried together in the oven and subjected to the same drying conditions to guarantee that all samples ended the process with the same moisture level. The influence of the position of the vial inside the oven was also tested and found to be negligible.

The test specimens were dried inside the vials to avoid contamination of the paper and were impregnated with new and degassed mineral oil just after extracting the vials from the oven. The vials were sealed with ptfe-silicone septum and stored until the beginning of the test (Fig. 6).

After preparation of the samples, and once impregnated with oil, the moisture content of the paper and oil, the polymerization degree of the paper and the markers in the oil (i.e., gases, furanic compounds, acidity and water) were analysed to set the starting point of the study.

The contact between oil and air was also considered, as happens in free-breathing transformers. To this end, a small head of air was left at the tops of the vials.
The ageing tests were performed in a laboratory oven under temperatures of 110, 120 and 130°C. The tests at 110 and 120 °C lasted for 12 weeks, while those at 130°C lasted for 6 weeks. For the temperature of 120 °C, four moisture levels from 1 to 4.2% were considered, while for 110 °C and 130 °C, just three levels were tested.

Two vials were introduced to the ageing oven for every tested point (moisture content and ageing time), and the polymerization degree, moisture content and markers of oil were monitored in both vials throughout the ageing tests.

A total of 204 vials were prepared, corresponding to the different moisture levels, ageing temperatures and sampling times. After the preparation stage, the initial samples were analysed to determine their moisture level, DP in paper and the initial condition of the oil. The vials were extracted every seven days for analysis in the laboratory. The DP and the water content of the paper were determined, and the dissolved gas, moisture and furanic compound contents in oil were analysed as well. The DP and 2FAL tests were carried out according to the IEC-60450 and IEC-61198 standards.

4 RESULTS

The DP and 2FAL values obtained during the experimental study were used to find a relation between 2FAL and DP and to determine whether that relation depends on the moisture level of the samples.

2FAL and DP were plotted for each tested temperature and moisture content; Figure 7 shows the graph found for the 120°C test. As can be observed, the relation between both variables follows an exponential
law that is clearly dependent on the MP of the paper samples tested. It must be remarked that various other authors also observed an exponential relation between 2FAL and DP [5-9].

The data obtained during the ageing tests performed at 120ºC were fitted to equation (7), yielding different parameters for each tested moisture level.

\[ 2FAL = A \cdot \exp(DP \cdot B) \]  

(7)

where 2FAL is the concentration of 2FAL in oil in ppm, and the DP is the degree of polymerization of paper.

![Figure 7](image_url)

**Figure 7.** 2FAL vs. DP obtained at 120ºC for specimens with different moisture contents. Experimental data and fitting curves.

Table 3 shows the parameters A and B obtained for the four cases and the regression coefficient \((R^2)\) obtained in each fitting process. Figure 7 shows the fitting curves.

**Table 3.** Parameters obtained when the data of 2FAL and DP for specimens aged at 120ºC are fitted to eq. (7) for the four tested moisture contents.

<table>
<thead>
<tr>
<th>MP (%)</th>
<th>A</th>
<th>B</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.43</td>
<td>-0.0052</td>
<td>0.93</td>
</tr>
<tr>
<td>1.2</td>
<td>32.9</td>
<td>-0.0060</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Analysing the data in Table 3, it can be observed that, except for the case of MP 4.2%, parameter A increases with the moisture content of the paper specimens, while parameter B has a slight variation that does not seem to follow any law.

Aiming to find a relation between the MP of paper and the 2FAL generation rate, an additional fitting process was carried out considering a constant value of B of -0.008, which is the average value of the parameter B values obtained for the different MPs, as listed in Table 3.

The values of A obtained in the second fitting process are shown in Table 4. As shown in this table, parameter A was obtained after fixing the value of parameter B, presenting a monotonous relation with the moisture content of the paper specimens that can be considered linear (Fig. 8).

**Table 4.** Fitting parameter A obtained for the different moisture contents when B=-0.08 is considered.

<table>
<thead>
<tr>
<th>MP (%)</th>
<th>A</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69.28</td>
<td>0.77</td>
</tr>
<tr>
<td>1.2</td>
<td>71.26</td>
<td>0.90</td>
</tr>
<tr>
<td>2.5</td>
<td>155.5</td>
<td>0.89</td>
</tr>
<tr>
<td>4.2</td>
<td>320</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Equation 8 was found to express parameter A as a function of the MP. The regression coefficient, $R^2$, of this relation is 0.986.

$$A = MP \cdot 78.98 - 23.3 \quad (8)$$

where MP is the moisture content of paper expressed in %.
Figure 8. Parameter A vs. moisture content of the paper and regression curve.

From the previous analysis, a general relation can be formulated (9) that relates the concentration of 2FAL with the polymerization degree of paper as a function of the moisture content of paper.

\[ 2\text{FAL (ppm)} = (\text{MP(\%)} \cdot 78.98 - 23.3) \cdot \exp(-0.008 \cdot \text{PD}) \quad (9) \]

The relation can also be expressed as (10) allowing the calculation of the DP of the paper as a function of the concentration of 2FAL and the moisture content of paper.

\[ \text{DP} = \frac{1}{-0.008} \log\left(\frac{2\text{FAL (ppm)}}{\text{MP(\%)} \cdot 78.98 - 23.3}\right) \quad (10) \]

Figure 9 shows the plotting of equation (9) for different paper moistures.
5. VALIDATION OF THE PROPOSED RELATION

Equation (10) was used to estimate the evolution of the DP throughout the experiments performed at different temperatures and on paper specimens with different moisture contents.

Firstly, the evolution of the DP during the accelerated ageing test performed at 120°C was estimated using equation (10) for the four moisture contents tested in this work. It must be noted that these data were used during the fitting period. To quantify the agreement between the estimated and measured data, the Normalized Root Mean Square Deviation (NRMSD) was calculated in each case using (11).

\[
NRMSD = \frac{RMSD}{DP_{\text{max}} - DP_{\text{min}}} \quad (11)
\]

where DPmax and DP_min are the maximum and minimum DP recorded during the experiment, and RMSD is the Root Mean Deviation, which can be calculated via (12).

\[
RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (DP_{est} - DP_{meas})^2} \quad (12)
\]
where n is the number of samples in an aging test.

The results of the model for all tested samples are shown in Table 5. Additionally, the models proposed by Chengdong (1) and De Pablo (2) were applied to estimate the DP from the 2FAL measurements. In the case of the Chengdong equation, the expression (13) derived from (2) was used.

\[
DP = \frac{1.51 - \log_{10}(2FAL_{ppm})}{0.0035}
\]  (13)

**Table 5.** Calculated errors when the DPs of the samples at 120 °C are estimated by equations (10), (13), and (2).

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>MP (%)</th>
<th>NMRS</th>
<th>Proposed relation</th>
<th>Chengdong</th>
<th>De Pablo</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>1.00</td>
<td>0.15</td>
<td>0.31</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>1.20</td>
<td>0.08</td>
<td>0.28</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>2.50</td>
<td>0.16</td>
<td>0.41</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>4.20</td>
<td>0.07</td>
<td>0.77</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>

As observed, the results of the proposed model are better than the results of the other authors’ models in all cases. In some of them, the improvement is very significant, as in the case of the estimation of the ageing process of the specimen with a moisture content of 4.2%. In this test, the concentrations of 2FAL obtained at the end of the ageing time were very high, and Chengdong’s equation predicted negative values of the DP, as shown in Figure 10.
Figure 10. Validation of the proposed model for the test specimens aged at 120 ºC with an MP 4.2%.

The data obtained with the test specimens aged at 130 and 110 ºC were also estimated by using the three models. The obtained errors are shown in Table 6. As can be observed in Tables 5 and 6, the De Pablo model performs well for the specimens aged with medium moisture contents (i.e., 2.5), while the Chengdong equation generally presents the lowest errors for MP approximately 1%, while both of them perform poorly at different MPs. This is probably due to the moisture content of the samples used during their experiments. Alternately it can be observed how the estimations of the proposed expression are accurate for all the cases included in the study. Figures 11 and 12 present some of the simulation cases.

Table 6. Errors calculated when the DPs of samples aged at 130 ºC and 110 ºC with different moisture contents are estimated using equations (10), (13) and (2).

<table>
<thead>
<tr>
<th>T (ºC)</th>
<th>MP (%)</th>
<th>NMRS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proposed Model</td>
<td>Chengdong</td>
</tr>
<tr>
<td>130</td>
<td>0.80</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>0.16</td>
</tr>
<tr>
<td>110</td>
<td>0.80</td>
<td>0.13</td>
</tr>
<tr>
<td>-----</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Figure 11.** Validation of the model for specimens aged at 130 °C with an MP of 1.2%.

**Figure 12.** Validation of the model for the test specimens aged at 110 °C with an MP of 0.8%.
Although the proposed model obtains more accurate values in the estimation of the DP of paper using the concentration of 2FAL, it should be remarked that the purpose of this work is not to provide an accurate estimation of the DP of the transformer paper or to criticize the classical models, such as De-Pablo’s or Chendong’s, which are very valuable and have been widely accepted. The paper is more focused on making note that the use of models that only consider the concentration of 2FAL to determine the DP of paper could lead to incorrect results under certain circumstances, such as the case shown in Figure 10. In the case of transformers with very high moisture contents, relatively higher 2FAL concentrations could appear, even though the paper has not reached its end-of-service life.

The application of equation (13) to diagnose the condition of a transformer would require estimation of the moisture content of its solid insulation.

The direct determination of MP is not possible in real transformers because of the unfeasibility of taking paper samples from the transformer’s active part. However, there are indirect methods that allow for a good estimation of the MP of field transformers. The most widely accepted techniques are those based on measuring and interpreting the dielectric response [19], such as Frequency dielectric response (FDS), Polarization and depolarization currents (PDC) or Recovery Voltage Measure (RVM). There are commercial pieces of equipment that allow for the performance of these measures in field transformers in a reasonable amount of time, and many companies currently incorporate these measures as maintenance tests for their transformers.

In addition, different authors [20, 21] have recently proposed new approaches for determine the approximate moisture in paper using on-line moisture-in-oil sensors and dynamic modelling or even moisture-in-paper sensors [22].

6. CONCLUSIONS

In this paper, the relation between the rate of generation of 2FAL and the moisture content of the solid insulation of a transformer is investigated.
A study was carried out to analyse the relation between the moisture content of oil and the concentration of 2FAL on in-service transformers, using a database with a large number of records to this end. The inspection of field data showed a clear correlation between these variables, proving that the evolution of the concentration of 2FAL in a transformer not only depends on the ageing condition of the insulating paper but also on the moisture content of the equipment. It is important to consider the relation between these two variables to avoid misinterpretations of the results of 2FAL analysis.

Aiming to obtain a deeper insight into this relation, a laboratory study was conducted in which paper samples conditioned with different moisture contents were subjected to accelerated ageing under different temperatures.

The results of the tests show a linear increase of the 2FAL generation rate with the moisture of paper. A relation has been found that allows the estimation of the DP of paper if the 2FAL concentration in oil and the moisture content of the solid insulation are known. The relation between the MP and 2FAL generation rate has been reported by other authors, but no mathematical relation has been proposed to date as far as the authors of this paper know.

The model was validated using a wide set of experimental data, and it was also compared with the models proposed by other authors, which do not take the influence of moisture on the generation of 2FAL into account. In all the tested cases, the calculated data show good agreement with the experimental measures, and in most cases, a considerable improvement was obtained when compared with the predictions of the models of other authors.

The inclusion of the MP in a 2FAL vs. DP model can lead to an improvement of the accuracy of the estimations. The use of a relation, such as that proposed in this paper, to diagnose field transformers would require estimating the moisture content of the solid insulation of the transformers.

The importance of the developed model is not so much that it provides an accurate value for the DP of the solid insulation of a transformer but that it attempts to correct incorrect estimations that might be derived if the classical models are used under certain conditions.
A good approach for diagnosing the condition of paper from the 2FAL analysis could be conducted by applying different models to analyse 2FAL field results, which will provide a certain range of DP values that the solid insulation of transformers should be located within.

There are additional factors, such as the presence of acids in the oil, which have been reported to have an influence on the 2FAL generation rate. It would be important to identify these factors and to find new relations or correction coefficients to include them in the interpretation of the 2FAL analysis.

As has been shown in this paper and in many other references, the interpretation of the results derived from transformer diagnostic techniques is not easy. A substantial number of influence factors come into play in the degradation process of a transformer, which are sometimes difficult to consider. It is highly advisable to avoid simplistic assumptions and to implement transformer global evaluation programmes, which combine different techniques and interpretation approaches. In the particular case of the furanic compound measurements, it is important to consider the comparison of the 2FAL concentrations in the transformer under study with the reference values [23] and to analyse the historical recordings of the transformer as the evolution of other markers that may have relation with the furane generation, as the moisture and the acidity of oil.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Economy and Competitiveness of Spain through the projects DPI2012-35819 and DPI2015-71219-C2-2-R, and by CEIS.

REFERENCES


