Statistical Study on the Reference Values of Furanic Compounds in Power Transformers

Key words: transformer aging, furanic compound, 2FAL, reference value, transformer insulation, transformer life assessment, mineral oil, Kraft paper

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This article presents a statistical study devoted to obtaining the reference values of 2FAL in power transformers.

Introduction

Power transformers are one of the most critical components of power systems, and failures often result in significant economic loss from the interruption of power and damage of assets. The establishment of maintenance programs that signal abnormal conditions in transformers is essential for the reliable operation of these equipments. However, in a competitive market, it is important to maximize investments by depleting the remaining life of the equipments before replacing them.

The end of life of a transformer comes about by aging of its solid insulation, which is mainly Kraft paper, pressboard, and wood, and these materials age mainly by hydrolysis reactions. Although transformer lifetimes are considered to be about 30 years, experience shows that some transformers remain in service for more than 50 years [1]. Aging of cellulosic insulation depends mainly on operating temperature, moisture, oxygen, and acids. The value of these factors depends on the operating conditions and maintenance practices, which are not always accurately quantified. Having a method to estimate the remaining life of a transformer is essential for owners to assess the risk of keeping a transformer in service or the necessity of replacing it.

Unfortunately, estimating the remaining life of transformer insulation is not an easy task because it is not possible to extract paper samples from the active part of the transformer to make direct determinations, and estimations are always based on indirect estimations. On the other hand, the transformer temperature is not homogeneous, so the condition of the paper varies within the transformer, which makes the analysis even more complex.

The determination of the furanic compounds content in the transformer oil is one of the more valuable methods to diagnose the aging condition of transformer solid insulation [2]. Unlike other markers, for example CO or CO_2, which are produced during the degradation of cellulosic insulation but also mineral oil, furanic compounds are exclusively generated as a by-product of the aging reactions of only cellulose insulation, and that makes the diagnosis more reliable.

The furanic content of oils has been studied for years, and some theoretical models have been proposed to estimate the polymerization degree of paper from the furanic content [3]–[5]. However, the analysis and the interpretation of the results is not so clear, and more work is necessary to make it a more useful method.

IEEE C57.104 and IEC 60599 standards provide interpretation methods and reference values for dissolved gas in oil, but these standards do not include recommendations for the interpretation of the results of furanic compounds. Recently, CIGRE WG D1.01.13 published "Furanic Compounds for Diagnosis" [6], in which some of the difficulties of the method are identified

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Table 1. Percentile Values of Furanic Compounds for the Database of 18,280 Records.				
Percentile	Furanic content[1] (ppm)			
	5HMF	2FAL	2ACF	5MEF
90th	0.1	0.9	0	0.1
95th	0.1	1.9	0	0.1
98th	0.2	4.1	0.1	0.2

[1]5HMF = 5hydroxymethyl-2furfural, 2FAL = 2furfuraldehyde, 2ACF = 2acetylfuran, and 5MEF = 5metyl-2furfural.

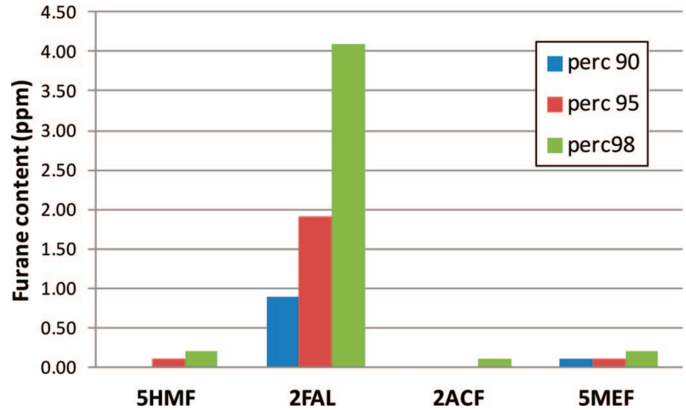

Figure 1. The 90th, 95th, and 98th percentile of 5hydroxymethyl-2furfural (5HMF), 2furfuraldehyde (2FAL), 2acetylfuran (2ACF), and 5metyl-2furfural (5MEF) calculated for the database of 18,280 records.

and recommendations are given to improve its potential use. The necessity of creating databases with typical values for different transformer populations was identified as one of the main goals in this field.

The Spanish company CEIS (Centro de Ensayos Innovacion y Servicios) has an accredited laboratory with more than 30 years of experience in testing dielectric materials and mainly electro-technical fluids. The experience of the laboratory in testing and helping to evaluate the results for the utilities of the Spanish electrical market has generated an important database with more than 28,000 registrants.

This article reports on the statistical values of furanic compounds dissolved in transformer oil. The 90th (alert), 95th, and 98th (alarm) percentiles of 5hydroxymethyl-2furfural (5HMF), 2furfuraldehyde (2FAL), 2acetylfuran (2ACF), and 5metyl-2furfural (5MEF) are calculated. As the presence and concentration of the compounds depends not only on the condition of the transformer, but also on its characteristics, the percentile values of the main furanic compound, 2FAL, are calculated for different transformer populations. The transformers in the database are divided according to their characteristics, and the percentiles are recalculated for the different groups determining the influence of the transformer characteristics in the 2FAL content in oil. All the criteria recommended by CIGRE WG D1.01.13 are considered in the analysis: age, voltage and power rating, cooling system, transformer type, and reasons for the analysis. Additionally, the typical growth rates of 2FAL are calculated for the whole database and for different populations classified according to transformer age.

Percentile Values of the Furanic Compounds of the Database

The database used in this study contains 28,597 records of oil analysis. These records were taken from 1993 to 2013 on 8,275 transformers, mainly free-breathing type, from more than 100 companies; from generation, transmission, and distribution of electrical power; and from industries, which also included many manufacturers of transformers.

Some of the records that did not include the analysis of furanic compounds were discarded, leaving 18,280 records for analysis, and all of which included values of the furanic compounds in oil and other markers, such as dissolved gasses, and complete physic-chemical analysis. Additional information about the transformers, such as their rated power, voltage, age, and cooling system is also included in the database.

All the furanic compound determinations were performed in the same laboratory according to IEC 61198. The concentration of the four most important compounds—5HMF, 2FAL, 2ACF, and 5MEF—was measured to one part per million.

Initially, the values of the 90th, 95th, and 98th percentile of 5HMF, 2FAL, 2ACF, and 5MEF were obtained. Table 1 and Figure 1 shows 2FAL as the furanic compound with the highest concentration. It can be seen that the concentrations of the other furanic compounds in most transformers are almost nil.

CIGRE WG D1.01.13 also shows the percentile values of 2FAL on a database of 30,000 records from 12 international laboratories and companies across North and South America, Europe, and Asia [5]. The comparison between the values calculated in this work and those proposed by CIGRE [5], shown in Figure 2, are within the same ranges, although the difference in the value of the 98th percentile differs.

CIGRE Brochure 494 [5] shows percentile values calculated from the database of the different laboratories and companies

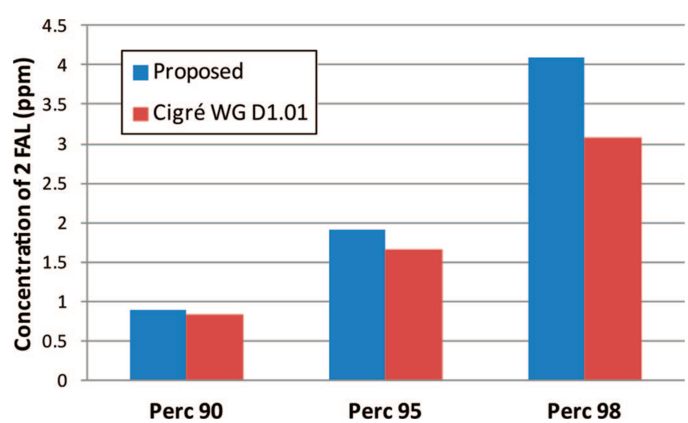

Figure 2. The 2furfuraldehyde (2FAL) 90th, 95th, and 98th percentiles calculated by Cigré verses values calculated in this work.

that participated in the study, finding significantly different values for each case. It is pointed out that the reference values calculated for populations of different countries may differ because of the differences in maintenance, loading practices, transformer design, and ambient temperature of each country. It should be noted that in Spain, most transformers are of the free-breathing type, and the use of thermally upgraded paper is not universal, which may have an influence on the typical furanic compound levels.

CIGRE has indicated that "a universal value for establishing normal levels for 2FAL should not be utilized" and has proposed "to subdivide the databases into subsets which represent similar equipment with regard to 2FAL generation and materials." WG D1.01.13 was not able to perform such subdivision because of the lack of information in the available records.

This task has been accomplished in the present work, using the database generated by CEIS, with 18,280 records. The study is focused on the study of 2FAL, which is the most abundant compound and the most suitable for diagnostic purposes.

Determination of the Percentile Values of 2FAL for Different Populations

Typical values of the furans-in-oil content depend on the transformer characteristics and on the operation mode. Therefore, the statistical evaluation of the data must be done considering different populations of transformers to obtain reliable reference values [5]. CIGRE WG D1.01.13 attempted to obtain typical values for different transformer populations taking into account the following factors:

- type of transformer,
- type of oil,
- type of oil-preservation system, and
- type of cooling system.

Additionally, other factors that may have a major influence on the aging of the cellulose are considered:

- thermal aspects,
- aging acceleration agents in contact with the cellulose (e.g., moisture and oxygen),
- design characteristics,
- oil processing, and
- type of paper used to insulate the transformers.

Finally, the working-group document points out that it is important to consider the motive of the analysis, dividing the data into routine analysis of transformers from data from transformers suspect of abnormal condition.

Unfortunately, the task could not be accomplished by WG D1.01.13, because not enough information was included in the records to do the classification [5].

In this work a percentile study has been done splitting the available database of 18,280 records into different categories:

- transformer age,
- rated power,
- rated voltage,
- transformer application,
- cooling mode, and
- motive of the analysis.

To state the validity of the proposed reference values, two important aspects of the Spanish transformer population should be highlighted.

- About 98% of the transformers included in the database are of the free-breathing type, because it is the common system used in Spain.
- All the transformers included in the study are insulated with nonupgraded Kraft paper and noninhibited mineral oil.

Classification by Transformer Age

Five age intervals were considered in this study. The numbers of records available for each category are shown in Table 2. It is interesting to note that the data are almost homogenously dis-

Table 2. Age Ranges Considered in the Study, Number of Records Available in Each Category, and 2FAL[1] Percentile as a Function of Transformer Age.

Transformer age (years)	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
0–10	4,622	25.28	0.2	0.4	0.9
11–20	4,528	24.77	0.7	1.7	3.7
21–30	4,517	24.71	1.1	2	4.3
31–40	3,540	19.37	1.8	3.4	6.1
>40	1,006	5.50	2.8	6.9	26.5
Unknown	67	0.37	—	—	—

[1]2FAL = 2furfuraldehyde.

Table 3. Number of Records Available of Transformers With Different Cooling Modes, and 2FAL[1] Percentiles for Each Mode.					
Cooling mode	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
ONAN	6,194	33.88	1.3	2.9	7.4
ONAN/ONAF	9,382	51.32	0.7	1.6	3.3
OFAF/OFWF	2,098	11.48	0.4	0.8	1.6
ODAF/ODWF	17	0.09	0.2	0.2	0.3
Unknown	589	3.22	—	—	—
[1]2FAL = 2furfuraldehyde.					

tributed within the different age ranges between 0 and 30 years. It should also be noted that 25% of the records in the database correspond to transformers older than 30 years.

The percentiles 90th, 95th and 98th of 2FAL obtained for each age range are shown in Table 2 and Figure 3. As can be seen, the percentiles increase sharply as the age rises.

Classification by Cooling System

The generation of 2FAL is strongly dependent on the temperature, which depends on the transformer cooling system. CIGRE WG D1.01.13 recommends calculating the 2FAL typical values for the various transformer cooling systems. The database was divided into categories according to the cooling mode of the transformers. The number of records of each category is shown in Table 3.

Figure 4 and Table 3 show the typical values calculated for the different cooling modes. As the cooling system is more efficient, the furanic content is lower. So ONAN-cooled transformers have the greater furanic content. The reason for that may be that the less efficient the cooling system is, the greater portion of the winding is subjected to elevated temperatures and so furans generation is higher.

Classification by Transformer Rated Power and Voltage

The database was divided according to transformer rated power and rated voltage to analyze the influence of transformer rating. The categories considered for each case are shown in Table 4 and Table 5, which include the number of records of the different categories. The 2FAL percentiles were calculated for each category, obtaining the results shown in Tables 4 and 5, and Figure 5.

It is evident that 2FAL typical values are greater for transformers with lower power and voltage ratings; the higher values are found on transformers with rated power lower than 25 MVA and rated voltage lower than 66 kV. To understand these results, an additional study was carried out splitting the database into categories according to power rating and age. These results are shown in Table 6.

The results obtained for the younger transformers (population 0–10 years) show the influence of the paper–oil ratio of the transformers, as large power transformers have a lower paper–oil ratio than small transformers [7]. It should be also highlighted here that the cooling system of a transformer is related with its rated power, and thus transformers with a power rating lower

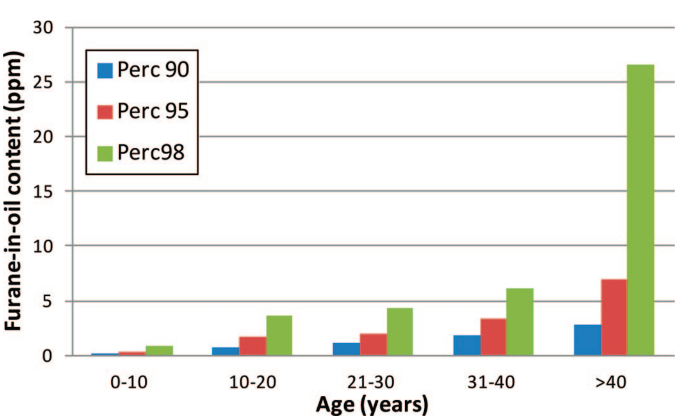

Figure 3. Percentiles (Perc) of 2furfuraldehyde as a function of transformer age.

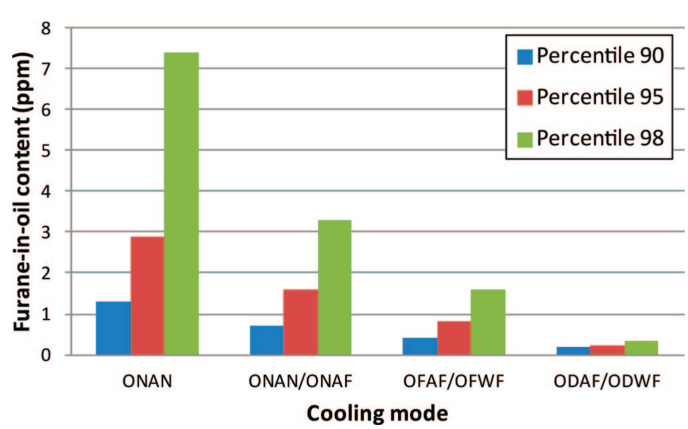

Figure 4. The 90th, 95th, and 98th percentile of 2furfuraldehyde for the different transformer cooling systems.

Table 4. Rated Powers Considered in the Study, Number of Records Available in Each Category, and 2FAL[1] Percentile Values.					
Rated power	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
MVA ≤5	5,691	31.13	1.3	2.6	6.3
5 < MVA ≤ 25	4,137	22.63	1.7	3.6	5.8
25 < MVA ≤ 100	3,524	19.28	0.5	0.8	1.7
100 < MVA ≤ 250	3,591	19.64	0.3	0.6	1.6
MVA >250	1,337	7.31	0.2	0.4	0.8
[1]2FAL = 2furfuraldehyde.					

Table 5. Rated Voltages Considered in the Study, Number of Records Available in Each Category, and 2FAL[1] Percentile Values.					
Rated voltage	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
kV ≤20	4,499	24.61	1.3	2.5	7.4
20 < kV ≤ 66	6,147	33.63	1.4	3.1	5.5
66 < kV ≤ 132	1,412	7.72	0.5	0.7	1.9
132 < kV ≤ 220	1,276	6.98	0.5	1.1	1.7
kV >220 kV	4,922	26.93	0.3	0.6	1.5
Unknown	25	0.14	—	—	—
[1]2FAL = 2furfuraldehyde.					

than 40 MVA are mainly ONAN transformers. So the high typical values of 2FAL percentiles of low power transformers and that of ONAN transformers are not independent events.

The comparison of the different populations proves the influence of the maintenance practices of the power transformers in the presence of 2FAL in the oil and, in consequence, in the degradation rate of the solid insulation. Large power transformers are subjected to more rigorous maintenance programs than small transformers, so the 90th percentile rises much more with transformer age than that of the low power transformers.

Classification by Transformer Type

The importance of classifying transformers according to their use is also in CIGRE WGD1.01.13, because the operation modes and typical loading profiles are very different depending on the application the transformer. Design differences also exist between these transformers.

The transformers in the database were divided into six categories according to their application: transmission, distribution, generation, renewable generation, railway traction, and industrial transformers. The industrial transformers were also divided into two groups according to their rated power. The number of records and percentile values are shown in Table 7.

In the initial database the number of distribution transformers was very scarce. To get a more complete picture of the 2FAL content in transformers of different industrial areas, the original database was complemented with 602 entries from a database provided by a utility. The percentile values were calculated according to all the available data.

Table 7 and Figure 6 show the 2FAL percentiles for each category. As can be seen transformers from utilities have the lowest furan contents. This is due to better maintenance practices. As the responsibility of the transformer is higher, the furan content is lower. So transmission transformer has the lowest furan content. On the opposite side are industrial transformers, especially those of lower ratings, where the maintenance policies are usually less demanding.

Motive for Analysis

Finally, the database population was divided according to the motive for the analysis. The categories considered were periodic revision, transformer failure, Buchholz trip, and oil treatment. Some records were also available from transformer commissioning.

The entries in each category are shown in Table 8. Unfortunately, a great number of the entries in the database do not

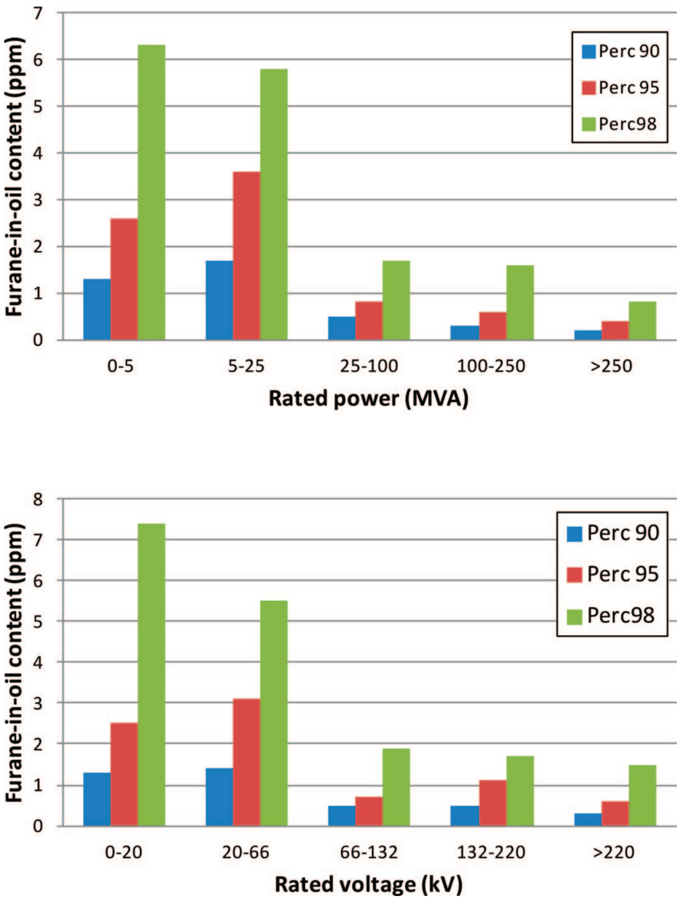

Figure 5. The 90th, 95th, and 98th percentiles of 2furfuraldehyde as a function of transformer rated power and voltage.

Table 6. 2FAL[1] Percentiles as a Function of Transformer MVA Rating and Age.

MVA rating	2FAL (ppm) 90th percentile	95th percentile	98th percentile
Transformer age 0–10 years			
MVA <5	0.3	0.8	1.7
5 < MVA ≤ 25	0.2	0.5	1.2
25 < MVA ≤ 100	0.2	0.4	0.7
100 < MVA ≤ 250	0.1	0.1	0.2
MVA >250	0.1	0.1	0.2
Transformer age 10–20 years			
MVA <5	1.1	2.5	5.0
5 < MVA ≤ 25	1.1	2.7	4.2
25 < MVA ≤ 100	0.4	1	2.0
100 < MVA ≤ 250	0.2	1.0	1.7
MVA >250	0.1	0.2	0.4
Transformer age 20–30 years			
MVA <5	1	1.8	3.3
5 < MVA ≤ 25	2.4	4.6	8.2
25 < MVA ≤ 100	0.6	0.9	2.2
100 < MVA ≤ 250	0.5	1.0	2.1
MVA >250	0.3	0.4	0.6

[1]2FAL = 2furfuraldehyde.

include information related to the motive for the analysis, and so, some of the percentiles displayed in the table were calculated with a low number of entries.

The values of the percentiles can be seen in Table 8 and in Figure 7. As was expected, no 2FAL was found in any of the commissioned transformers. On the other hand, although the higher 90th percentile appears in transformers in which the reason for the analysis was a failure, the 95th and 98th percentiles of these transformers are not very high. The greater 2FAL levels (95th and 98th percentile) appear in the case of routine revisions.

Furan Growth Rate

When examining the oil analysis data, it must be verified that 2FAL values are within normal limits. In addition, the data must also be checked for the furan growth rate, as this is indicative of the rate of paper aging and, therefore, if transformer failure is likely. For this reason it has been considered necessary to conduct a study on the growth rates of 2FAL using the records included in the database.

In this study, the percentiles of the 2FAL growth rates were calculated. General values based on the entire database were obtained and also typical values for different transformer ages.

Growth Rate Calculation Procedure

None of the present standards include recommendations on the calculation of typical growth rates of gases and furans in transformer oil. As such, a method was developed that guarantees the reliability of the obtained values. In the procedure, the database was filtered as follows.

1. Records from transformers with analysis after commissioning less than one year were not considered.
2. Records from transformers having less than four consecutive analyses were not considered.
3. Records from transformers with only a few available 2FAL records also were not considered.

Filters 1 and 2 were applied to the CEIS database. After the first filter, 17,746 records from 3,778 transformers of 154 companies remained, and after the second filter, 13,398 records corresponding to 1,253 transformers from 68 companies remained.

Two different cases were considered to obtain the growth rate:

Table 7. Number of Records Available of the Different Transformer Applications and 2FAL[1] Percentiles.					
Transformer application	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
Transmission	3,107	17.00	0.4	0.7	1.7
Distribution[2]	69 + 602	0.38	0.8	1.5	3.0
Generation	5,349	29.26	0.5	1	2
Renewable generation	45	0.25	3.5	4	4.1
Railway traction	416	2.27	0.6	0.9	1.3
Industrial					
MVA <10	4,715	25.79	1.9	4	8.3
MVA >10	4,366	23.88	1	2.3	4.9
Total	9,081	49.68	1.5	3.2	6.5
Others and unknown	213	1.17	—	—	—

[1]2FAL = 2furfuraldehyde.
[2]To get a more complete picture of the 2FAL content in transformers of different industrial areas, the original database was complemented with 602 entries from a database provided by a utility.

Table 8. Number of Records Available for the Various Motives for Analysis and Percentile Values.					
Motive for analysis	No. of transformers	%	2FAL (ppm)		
			90th percentile	95th percentile	98th percentile
Routine revision	8,841	48.36	0.9	1.8	3.9
Failure	82	0.45	1.8	1.9	2.0
Buchholz trip	100	0.55	0.9	1.7	2.1
Commissioning	16	0.10	0	0	0
Unknown	9,241	50.55	—	—	—

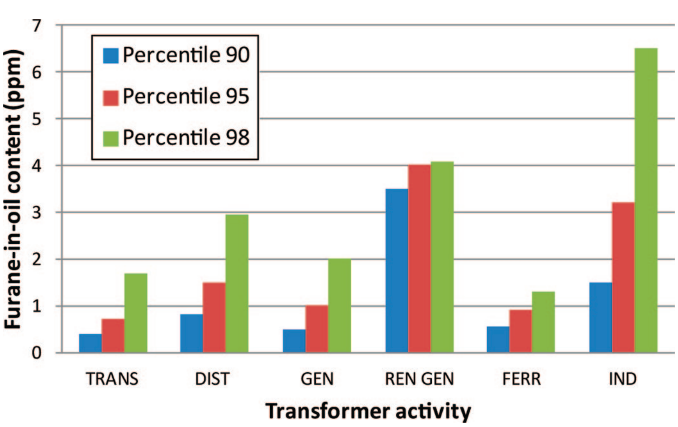

Figure 6. The 90th, 95th, and 98th percentiles of 2furfuraldehyde for the various transformer applications. TRANS = transmission, DIST = distribution, GEN = generation, REN GEN = renewable generation, FERR = railway traction, IND = industrial.

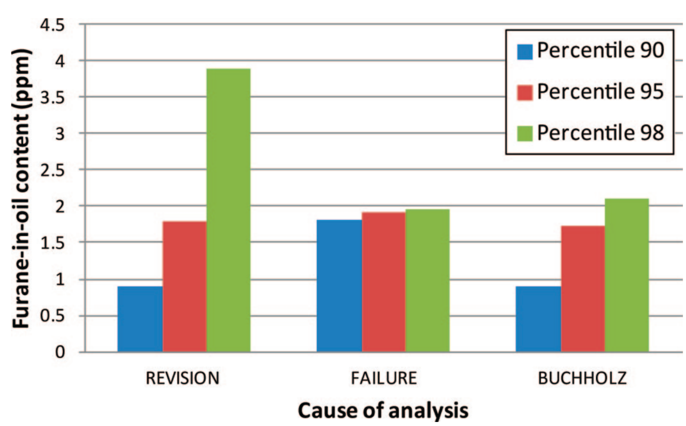

Figure 7. The 90th, 95th, and 98th percentiles of 2furfuraldehyde as a function of the motive for analysis.

Table 9. Main Percentiles of 2Furfuraldehyde Growth Rates.	
Percentile	**ppm/year**
90th	0.10
95th	0.25
98th	0.52

- When all the values of 2FAL recorded for a particular transformer are lower or equal to 0.2 ppm, the growth rate obtained is the maximum value of 2FAL divided by the transformer age.
- For transformers having at least one of the 2FAL records higher than 0.2 ppm, the slope was sectionalized.

It must be highlighted that 53 out of 1,253 transformers (4.2%) had reclaimed oil within the analyzed period. Also, only 22 transformers (1.8%) exceeded the threshold of 8 ppm for 2FAL. When the 2FAL value exceeded the threshold, it was considered that an internal failure had occurred in the transformer and 2FAL growth rates do not correspond to a healthy transformer.

General Values of the Growth Rate

Table 9 shows the 90th, 95th, and 98th percentiles of the 2FAL growth rates in ppm per year calculated according to the developed procedure. As can be seen, the 90th percentile is about 0.1 ppm/year, which means a 2FAL content of 3 ppm after 30 years of service.

Growth Rate for Different Age Populations

Some authors have proposed models to estimate the degree of polymerization of the transformer insulation from the content of 2FAL. In most models a logarithmic relation between degree of polymerization and the concentration of 2FAL in oil is considered, what would mean that the generation of 2FAL is more abrupt during the last part of the life of the insulation [3], [6], [8].

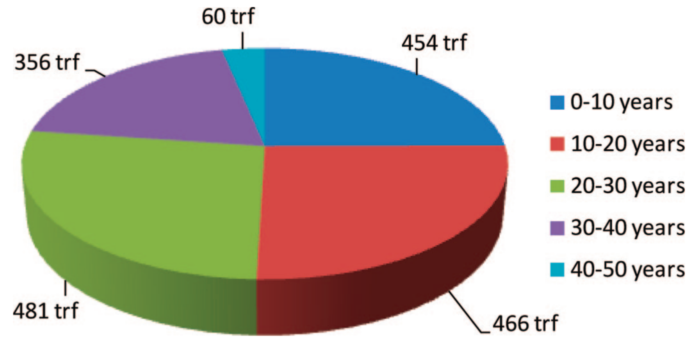

Figure 8. Distribution according transformer age (in years).

To study the dependency of the 2FAL generation rate with transformer age, the database was divided into populations according to transformer age. It should be noted that data for each transformer corresponded to very different dates, and as the growth rate depends on transformer age, different growth rates are possible.

The distribution of data according to the age of the transformer is shown in Figure 8, and the typical growth rates calculated using these data are shown in Table 10.

To determine whether the growth rate depends significantly on the transformer owner, and therefore on the type of transformers and the maintenance protocols applied to them, as Cigré suggests [6], the growth rates of 2FAL of the transformers of one particular company were studied.

Data of 241 transformers belonging to the company X were analyzed, determining the reference values of the 2FAL growth rate for populations of different age. The obtained values and the numbers of transformers of each group used to do the calculations are shown in Table 11.

Table 10. Growth Rate (ppm/year) of 2Furfuraldehyde as a Function of Transformer Age.					
Percentile	**0–10 years**	**10–20 years**	**20–30 years**	**30–40 years**	**40–50 years**
90th	0.05	0.11	0.13	0.19	0.14
95th	0.11	0.25	0.24	0.36	1.10
98th	0.26	0.59	0.52	0.60	2.21

Table 11. Growth Rate (ppm/year) of 2Furfuraldehyde as a Function of Transformer Age for Company X, and Number of Recordings Used for the Calculation.						
Item	**0–10 years**	**10–20 years**	**20–30 years**	**30–40 years**	**40–50 years**	**All ages**
90th percentile	0.01	0.01	0.04	0.07	0.03	0.03
95th percentile	0.02	0.03	0.07	0.14	0.04	0.05
98th percentile	0.02	0.04	0.22	0.23	0.41	0.09
Number of transformers	109	68	71	75	28	241

The company X is devoted to the generation of energy, and therefore, the transformers included in the study are large units that are subjected to exhaustive maintenance programs. These programs include the performance of complete oil analysis, including physical-chemical, dissolved gasses, and furanic compounds, at least once a year and more frequent tests and further maintenance operations if abnormal results are found. In the case of transformers of nuclear power plants, that are also included in the selected population, the maintenance programs are even more exigent, being monthly or quarterly oil analysis.

Comparing Tables 10 and 11, it can be seen that the growth rates of 2FAL for the transformers of the company X are up to 15 times lower than that calculated for the complete database as a result of a better program of transformer maintenance.

Conclusions

The study examined typical values of 2FAL as a function of transformer characteristics. The database was divided according to transformer age, cooling system, rated voltage and power, transformer application, and the reason for the analysis, and the 90th, 95th, and 98th percentiles were calculated for each transformer category as proposed by CIGRE WG D1.01.13.

The following conclusions were extracted from the study:

- The results showed a significant influence on transformer age.
- Factors such as power and voltage rating have an influence due to different oil–paper ratios among the transformers and better maintenance programs for large transformers.

Typical growth rates of 2FAL were calculated using a developed method. Growth rates of 2FAL are also obtained for transformer populations according to age, as age has a major influence in the presence of 2FAL.

Also the quality of the maintenance program and the transformers characteristics seem to have an importance in the determination of the reference values or growth rate of furfural.

Acknowledgments

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