

# Transformer lifetime management by analyzing the content of furan and gas dissolved in oil

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**Abstract.** In order to see the transformer insulation status, the temperature profile, the degree of polymerization (DP), the furan compound content, the carbon dioxide, and carbon monoxide concentration are monitored. By evaluating the degree of polymerization (DP) of the cellulose paper insulation and furans in the determination of the insulating oil, it can estimate the lifetime of the transformer. Analysis of cellulose insulation paper to see the degree of polymerization (DP) can be performed safely only when the transformer is interrupted. However, being a non-invasive test, determination of furane content in an oil-insulating oil is often used as an alternative method for measuring the DP average of insulation paper. In order to analyze the technical condition of a transformer, furan content in oil should be used and interpreted as a primary chemical indicator in conjunction with the results of carbon oxide from the dissolved gas analysis, the acidity and moisture results from the chemical tests, the methanol content from the chromatographic tests and other monitoring techniques.

## 1. Introduction

Power transformers are among the main cost elements of the power industry, with transmission and power generation functions. They are very reliable devices and with the passage of time they can be defective, and so we can denote this mode of failure, the end of life of the transformation [1]. Organic materials used in the transformer are subject to aging processes which lead to the gradual degradation of their physical, chemical and electrical properties. The most important of these organic materials is the composite insulation system, ie cellulosic materials (mainly paper and cardboard) impregnated with insulating liquid (mainly mineral). The aging of cellulose/oil insulation systems is based on three main processes.

The first process that causes aging is pyrolysis, which is initiated by temperature as the main driving force behind the chemical reactions [2,3]. Following the other hydrolysis processes, initiated by the presence of water and oxidation. Thus cellulose lifetime can be maximized by careful monitoring and maintenance. Proper monitoring of the state of the aging parameters of the insulation system could be achieved by improving the replacement planning, thus avoiding the consequences of a rapid and unforeseen transformer failure.

The lifetime of cellulose insulation is determined by mechanical strength and the best method for assessing this property is the degree of polymerization (DP) [4]. From the literature, it follows that when the DP is below 250, the end of life is reached and this DP value indicates the minimum power considered necessary to resist a short circuit.

Since it is not possible to monitor the DP values of transformers in operation, laboratory models simulating aging of paper/oil insulation under accelerated conditions allow a feasible way to analyze the effect of different oils and key aging parameters: temperature, oxygen, and water on cellulose aggressiveness [5]. Due to the increase in the furans content in the insulating oil and the moisture content in the solid insulation, we decided to perform the DP test to find out the state of solid insulation degradation.

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There are a lot of power transformers from electrical utilities around the world that are approaching the end of their design life. The state of degradation of the insulation materials in transformers is a major concern for these old transformers, degrading them at higher operating temperatures in the presence of oxygen and humidity. Currently, a number of modern diagnostic techniques are used to evaluate the isolation status of older transformers. Frequency analysis is used for transformer oil, dissolved gas analysis (DGA), polymerization measurement and furan analysis by high-performance liquid chromatography (HPLC) [6,7].

### Case studies

In various articles from the literature, there are presented case studies of the diagnostic status of the transformer where the presence of furan is a primary indicator of chemical degradation of insulating paper. Interpretation of the results of this analysis must be carried out only in conjunction with other analyses and determinations, with the operating regime (in particular by monitoring the oil temperature of the transformer) and based on consistent periodic analyses [8].

Due to the complexity of cellulose degradation mechanisms and the multitude of factors that can influence the process, the dependence between the concentration of furan compounds in the insulating oil and the lifetime of the transformer is not fully elucidated. Here are some of the most interesting aspects of bibliographic research done.

Factors that have a significant influence on the formation of 2-furaldehyde (which is the most stable and soluble furan) in oil it has:

- the initial concentration of 2-furaldehyde in the insulating oil is determined by the ratio of the formation/degradation rate to a certain temperature;
- the presence of moisture significantly influences the distribution of furan compounds between paper and oil (favors 2-FAL formation);
- temperature influences the formation/degradation of 2-furaldehyde. Operating temperature variations due to different load conditions (cyclic or constant) significantly influence the formation of furans;
- the type of oil is also very important. Additive oil inhibitors have a certain protective effect on paper thermosetting and lead to slowing down the formation of furan compounds, compared to non-additive oils;
- heat treated paper produces a lower amount of furan compounds than normal Kraft paper;
- transformer type (paper/oil ratio) and cooling conditions are very important. Increasing the amount of paper involves the formation of furans (different temperatures of exposure);
- changing the oil causes a lower furnace content over a period of time. But, as an equilibrium reaction, the initial concentration will be reached again.

Internationally, there are more studies on the model used to obtain a correlation between oil content furans and the degree of polymerization of paper. There is still no single correlation, supported by all groups of researchers who have dealt with these studies [9].

However, there is a common element, all the accepted relationships correlate the degree of polymerization of the paper with the furfural or 2-furaldehyde (2-FAL) content of the oil [7]. This is due to the fact that all the other compounds of furan resulting from the degradation of the paper: 5-hydroxymethylfurfural (5-HMF), 5-methyl furfural (5-MEF) and 2-acetylfuran (2-ACF) are less stable than 2-FAL under the specific conditions of the transformer, and tend to decompose in a relatively short time in 2-furaldehyde (2-FALs) [10].

Chendong s.a. [11], found the following linear relationship between the furfural concentration in logarithmic scale and the degree of polymerization:

$$\log [2\text{-FAL}] = 1,51 - 0,0035 \times \text{DP} \quad (1)$$

where: 2-FAL – the concentration of 2-furaldehyde, mg/l  
DP – degree of polymerization

Experiments by De Pablo [11,4] showed that not all paper degrades at the same speed. They found the following relationship between the furans concentration and the degree of polymerization:

$$\text{DP} = 7100 / (8,88 + 2\text{-FAL}) \quad (2)$$

Pahlavanpour [11], found the following relationship between furan concentration and degree of polymerization:

$$DP = 800 / [(0,186 \times 2\text{-FAL}) + 1] \quad (3)$$

Studies of Mulej in Slovenia [12] established equations (4) and (5) correlating the concentration of furfural degree of polymerization of paper, depending on the embodiment of the experiments.

Equation (4) was obtained based on the experimental results of artificial aging performed in several laboratories

$$\log 2\text{-FAL} = - 0,0023 \times DP + 1,237 \quad (4)$$

At the same time, the degree of polymerization and the content of furfural were determined for samples of paper and oil taken from 25 partially open transformers, which led to equation (5):

$$\log 2\text{-FAL} = - 0,0026 \times DP + 0,727 \quad (5)$$

The first research found that the concentration of 2-furaldehyde in oil obtained by artificially aging paper is higher than that determined in the oil in the working transformer, whose paper has the same degradation [12, 13].

The results of the study are presented in Table 1. Also, Table 1 includes the values for the degree of polymerization of the paper based upon the calculation performed by specialists ICEMENERG using the above relations.

**Table 1.** Correlation of degree of polymerization with furans content

Nr. crt.	Equipment	Content of dissolved CO, ppm	2-FAL content, ppm	IEC 450	The degree of polymerization, calculated according to the respective IEC 450 equations				
					ec. 1 Chendong	ec. 2 Pablo	ec.3 Pahlavanpour	ec.4 Mulej	ec. 5 Mulej
1	Trafo 132/66/11 Kv	4573	9,0	237	158,8	397,1	299,2	122,9	-
2	Trafo 66/11 kV	5495	12,0	108	124,1	341,3	247,5	68,6	-
3	Trafo 66/11 kV	5887	7,5	298	182,4	435,6	310,0	157,4	-
4	Trafo 132/66 kV	1541	6,6	345	197,3	461,0	359,1	181,5	-
5	Trafo 220/132 kV	417	1,0	780	431,4	724,5	774,5	537,8	279,6

The analysis of the resulting data presented in Table 1:

- the values obtained for the degree of polymerization calculated with the above formulas show a variation over a very wide range from the values determined according to IEC 450 [14];
- the values of the degree of polymerization calculated by the Pahlavanpour formula are the closest to the values determined according to IEC 450, then come to the values calculated with the formulations of De Pablo, Chendong, Mulej (formula 4) and Mulej (formula 5);
- the content of 2-furaldehyde (2-FAL) determined in the oil is lower, the degree of polymerization calculated with the formula is any more real than the value determined by IEC 450;
- it is noted that the best correlation between the oil furans content and the degree of polymerization of the coating was obtained using the formula of Pahlavanpour;
- it is recommended to periodically determine the furans content during the operation of the transformer for the cumulative monitoring of the insulating cellulose state;
- the furans content should be used and interpreted as a primary chemical indicator in conjunction with the results of oil-gas analysis and other monitoring techniques;
- for values of 2-furaldehyde content higher than 1 ppm, Mulej's formula 5 can not be applied.

## 2. Results and discussions

To establish the preliminary limit of furans in the insulating oil was sampled and analyzed by multiple transformer oils. In Table 2, are given the transformers from which oil samples analyzed were taken and the type of oil (without additives/additives) with which they are equipped.

**Table 2.** Types of equipment

Nr. crt.	Equipment	Type oil
1	T 1 – st. 400 kV Pelican – ST Bucharest	Tr 25A
2	Trafo – CHE Tismana – SH Tg. Jiu	Tr 30.01
3	T 2 – st. 400 kV Brasov Nord – ST Sibiu	Tr 25A
4	AT 200 – st. 400 kV Iernut – ST Sibiu	Tr 25A
5	Trafo 1, CET Grozavesti	Tr 30.01
6	Trafo 400 MVA, Complex Energetic Rovinari	Tr 30.01

Oil samples were analyzed in two locations:

- in the Oil Laboratory of ICEMENERG, where physicochemical and electrical analyzes were performed;
- in the chemical laboratory, where the determined content of furan compounds.

For some equipment, there was introduced and dissolved gas analysis (the content of CO<sub>2</sub> and CO) in conjunction with oil which subsequently results in the determination of the content of furans.

The analysis of the characteristics determined and presented in Table 3 results in the following:

- both additive electro-insulating oils (Tr 25A) and unadapted (Tr 30) were analyzed;
- transformer life ranges in a wide range, between 4 ÷ 32 years;
- the analyzed oils showed different stages of degradation, from very low degradation - oil from the AT 200 Iernut to an advanced degradation - the oil from the trafo 1 CHE Tismana and the trafo 400 Rovinari;
- the total determined furans content is between 0.01 ppm ÷ 6,079 ppm;
- furans in the highest concentrations are 2-furaldehyde (0 ÷ 2,548 ppm) and 5-hydroxymethylfurfural (0 ÷ 5,862 ppm);
- based on the analyses performed, the dependence of the furans content on the degree of degradation of the oil was not revealed.
- using the above-mentioned formulas, the degree of polymerization of the solid insulation in the transformers for which the furan content of the oil was determined was calculated.

The results obtained are summarized in Table 3.

**Table 3.** The calculation of the content based on the degree of polymerization of 2-FAL

Nr. crt.	Equipment	2-FAL, ppm	Degree of polymerization calculated with the formulas:		
			ec. 1 Chendong	ec. 2 Pablo	ec. 4 Mulej
1	T 1, st. 400 kV Pelicanu	0,00	-	806,8	-
2	AT 200, st. 400 kV Iernut	0,00	-	806,8	-
3	Trafo 1, CHE Tismana	0,22	619,3	787,1	823,7
4	T2, st. 400 kV Braşov N.	0,05	803,2	802,3	1103,5
5	Trafo 1, CET Grozavesti	0,349	562,1	776,0	736,6
6	Trafo 400 MVA, Complex Energetic Rovinari	0,146	670,2	793,7	901,2

The analysis of the data contained in Table 3 shows that for the same content from 2-furaldehyde (2-FAL) different values are obtained for the degree of polymerization, according to the calculation formula applied.

It is noted that until the time of writing, the degree of polymerization of the insulating paper according to IEC 450 was not determined because the transformers from which the paper samples had to be taken were not yet out of operation.

### 3. Conclusions

The presence and concentration of furan compounds in the oil are dependent upon:

- operating temperature;
- type transformer;
- type of oil;
- the type of paper.

The following furan compounds result from the degradation of the paper: 2-furaldehyde (2-FAL), 5-hydroxymethylfurfural (5-HMF), 5 methyl furfural (5-MEF) and acetylfuran (ACF). Of these, the most stable is 2-FAL, the other furans tend to decompose in a relatively short time furfural.

The factors that have an influence on the formation of 2-furfural in the insulating oil are:

- the actual concentration of furfural in the insulating oil is a balance between the rate of formation/degradation at a given temperature.
- moisture content has a very important influence, as they influence the distribution between the paper and the oil furan compounds;

There are many studies on the patterns used to get a correlation between the oil content of the furans and the degree of papermaking. However, there is no correlation accepted by all groups of researchers who have dealt with these specific studies.

It is recommended to periodically determine the furans content during transformer operation for the cumulative monitoring of the insulating cellulose state.

Furans content must be interpreted as a chemical used in conjunction with the primary analysis results of gas dissolved in oil and other monitoring techniques.

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