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# FUZZY LOGIC SYSTEM BASED ON DISSOLVED GAS ANALYSIS AND FURAN ANALYSIS FOR POWER TRANSFORMER FAULT DIAGNOSIS

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*This paper presents a diagnosis fuzzy logic software system implemented in LabVIEW, based on DGA (Dissolved Gas Analysis) and are making the correlation with the analysis of furan derivatives concentration for a better accuracy of transformer faults prediction. The developed system allows the values resulting from the laboratory chemical analysis to be entered in a MySQL database, use the fuzzy logic and LabVIEW software development to implement the DGA and furan analysis methods, enters the results in a MySQL database, generates automatic reports, sends emails with reports to default addresses and provides string packages with the results obtained for an OPC UA (OLE Object linking and embedding for Process Control Unified Architecture) server for integration into the associated SCADA (Supervisory Control and Data Acquisition) system of an electrical substation. The validation of the presented system consists in testing on a very large number of power transformers of the Romanian Hydro-Power System. The results have proven the consistency between the software decision and the expert evaluation decision.*

**Keywords**: DGA, furan analysis, fuzzy logic, diagnosis system, power transformer

## 1. Introduction

In order to achieve greater safety in the power supply of consumers, it is necessary to have knowledge of the technical working condition of electrical equipment used in the transmission and distribution networks. The operation of the modern power system relies on power transformers, which are the most critical and expensive equipment. Faults must be determined in the early stages, in

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order to avoid failures which can lead to interruptions in the supply of electrical installations. [1-3].

In practice, the life of the insulation is the parameter which limits the life of power transformers. The insulation systems of power transformers, especially the paper and the mineral oil will be subjected to degradation due to permanent or accidental overstress. The operation of transformers is influenced by combined stresses (electrical, thermal, mechanical, and environmental), affecting mostly the main insulation (paper-oil). The ageing of the main insulation is influenced by temperature, which is the most important parameter in transformers. Overloading, and respectively dielectric losses or core losses can be determined by the heat density of the insulation system [4-11].

Not only electrical, thermal, mechanical stresses affect transformers, but also other stresses which are specific to the operating environment of the equipment: humidity, atmospheric oxygen, ultraviolet and nuclear radiation, industrial pollution, microorganisms, etc. The paper-oil insulation condition can be detailed by using the DGA and furan compounds analysis, thus improving the condition monitoring of electrical equipment, and presenting a great amount of data on the phenomena affecting such equipment [12-14].

In case of gases generated by several faults in transformers, due to the fact that the gases may not correspond to the predefined codes, the relation between the different gases becomes too complex. The arcing, overheating and partial discharge fault affecting the main tank in power transformers is detected by using this type of DGA. There are unique combinations of each of separate gases, called key gases for different fault temperatures. The types of faults are indicated by the ratios of certain key gas concentrations [15-17].

Fuzzy Logic can be used to diagnose such cases. Fuzzy logic with fuzzy-logic IF-THEN rules firing scheme have been used to analyze the working condition of transformers [18-20]. The paper is an extension of work of [17] and the novelty is that for a better accuracy of early fault diagnosis, a diagnostic technique has been used combining the Key Gas method, the IEC Ratio method, the Roger's Ratio method, the Dörnenburg Ratio method, Duval's Triangle method, Total Dissolved Combustible Gas (TDCG) method, which are correlated with the analysis of furan derivatives concentration, in particular 2-furaldehyde (2-FAL). Further, the diagnosis system proposed in this article allows the values resulting from the laboratory chemical analysis to be entered in a database, uses a LabVIEW software development and fuzzy logic based system, to implement the DGA and furan analysis methods, enters the results in a database, generates automatic reports, sends emails with reports to predefined addresses and provides string packages with the results obtained for an OPC server for integration into the associated SCADA system of an electrical substation.

The paper is organized as follows: Section 2 describes the methods for dissolved gas analysis and furans derivate concentration analysis. Section 3 presents the power transformer fault diagnosis system based on the dissolved gas analysis and furan derivatives analysis. The validation of the presented system is described in Section 4 by testing on a very large number of power transformers of the Romanian Hydro-Power System. The paper ends with a section of conclusions describing the main aspects and advantages of the developed system, some conclusions will be made, and some ideas will be pointed out for continuation of work.

## 2. Dissolved gas analysis and furan derivatives concentration analysis

The most important tool in determining the condition of a transformer is the dissolved gas analysis, which is the first to indicate whenever a problem occurs. It can be used to identify damage to the insulation and oil, overheating, the hot-spots, partial discharges and arcing. The “health” of the transformer is mirrored by oil “health”. The dissolved gas analysis is based on lab testing of transformer oil samples. The individual and total fuel gas generation rates (TGG) are the most important parameters [5-8]. The DGA consists of the following steps: sampling of oil from the unit and extraction of the dissolved gas from the oil using the gas chromatography method; gas concentration detection and fault analysis by applying proper diagnostic tools for identifying the causes of faults. The amount of accumulated gases is not as important as the rapid increase of fuel gases and their production rate for the assessment of transformers. The high-performance liquid chromatography (HPLC) method is used to perform the analysis of the content of furan derivatives dispersed oil [5].

The “furan compounds” consist of a family of compounds, all of which should be defined as furan derivatives. The HPLC will be used to analyze the following five different furans and the most common problems causing them to occur: 5-H2F (5-hydroxymethyl-2-furaldehyde) caused by oxidation of the paper (aging and heating); 2-FOL (2-furfurol) caused by high humidity in paper; 2-FAL (2-furaldehyde) caused by overheating; 2-ACF (2-acetylfuran) caused by lightning (seldom found during analysis); 5-M2F (5-methyl-2-furaldehyde) caused by severe local overheating (hot-spot) [1-3].

Most furan derivatives resulting from the degradation of cellulose macromolecules chains are absorbed by the paper. The dissipation coefficient at the given temperature and the paper water content determine the absorbed quantity of furan. It can be said that of all furan derivatives caused by the degradation of paper insulation, the 2-furaldehyde is the only one being dissipated in large amounts in oil, considering that the dissipation coefficient of 2-furaldehyde reaches 0.83 at a certain temperature and a certain content of water, meaning that 83% is dissipated in oil. The degree of polymerization (DP) of the electrical insulation paper can be monitored best by using the 2-FAL, based on its properties of being dispersed in oil in large amounts and its thermal stability in relation to the other derivatives [14].

### 3. Fuzzy fault diagnosis system for power transformer

This implemented system would be used for the diagnosis of power transformers and is developed based on the six most widely used dissolved gas analysis methods and the analysis of the furan derivatives concentration method and can provide more detailed information about the transformer conditions based on the fuzzy logic control. The architecture of the power transformer fault diagnosis system based on the dissolved gas analysis and furan derivatives analysis is shown in Fig. 1.

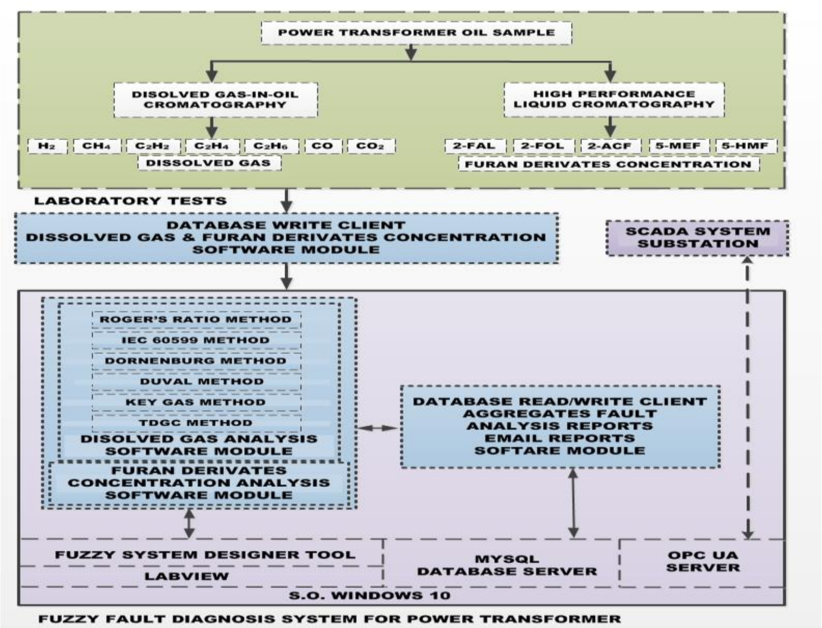


Fig. 1. Architecture of fuzzy system for fault diagnosis for power transformers

The diagnosis system was implemented using the LabVIEW software development and fuzzy logic system, for the implementation of the DGA and furan analysis methods. The results which represent the faults generated by the diagnosis module are entered as fault codes into a database, thus contributing to creating records of the transformation unit. The Database Read/Write Client Module generates automatic reports, sends emails with reports to default addresses and provides string packages with the results obtained for an OPC UA server for integration into the associated SCADA system of an electrical substation [23, 24]. The development of the fuzzy system for fault diagnosis in power transformers involves three processes namely fuzzification, fuzzy inference, and defuzzification. The Fuzzy System Designer from LabVIEW environment is used for this purpose. LabVIEW contains a comprehensive set of tools for data acquisition, analysis, display, and storage, as well as tools to help us troubleshoot the written code [25]. The fault codes for the analysis methods are presented in Tables 1-8 [3-5], [8], [12].

*Table 1*

**Fault code for Key Gas Method [4, 5], [8]**

| Code | Fault |
|---|---|
| DP | *Partial discharges.* |
| D2 | *High energy discharges, electric arc formation (determine if defective gas diffuses into the tank, starting from a load-change switch).* |
| T | *Thermal fault of oil.* |
| T1 | *Cellulose degradation caused by an electrical fault. (It is recommended to analyze the furan compounds).* |
| T2 | *Cellulose degradation caused by an electrical fault. (It is recommended to analyze the furan compounds).* |

*Table 2*

**Fault code for IEC Ratio Method [4, 5], [8]**

| Code | Fault |
|---|---|
| N | *No fault: Normal deterioration.* |
| D1 | *Partial discharges of low energy density (Corona)* |
| D2 | *Partial discharges of high energy density, possibly with tracking.* |
| D3 | *Partial discharges of low energy with floating potential.* |
| D4 | *Partial discharges of high energy density involving solid insulation.* |
| T1 | *Thermal fault of low temperature range: $t < 150^0C$* |
| T2 | *Thermal fault of low temperature range: $150^0C < t < 300^0C$* |
| T3 | *Thermal fault of medium temperature range: $300^0C < t < 700^0C$* |
| T4 | *Thermal fault of high temperature: $t > 700^0C$* |

*Table 3*

**Fault code for Roger's Ratio Method [4, 5], [8]**

| Code | Fault |
|---|---|
| N | *No fault: Normal deterioration.* |
| D1 | *Partial discharges of low energy density (Corona)* |
| D2 | *Partial discharges of high energy density, possibly with tracking.* |
| D3 | *Partial discharges of low energy with floating potential.* |
| D4 | *Partial discharges of high energy density involving solid insulation.* |
| D5 | *Discharges of low energy: flashover without power follow through.* |
| D6 | *Discharges of low energy: continuous sparking to floating potential.* |
| D7 | *Discharge of high energy: arc with power follow through.* |
| T1 | *Thermal fault of low temperature range: $t < 150^0C$* |
| T2 | *Thermal fault of low temperature range: $150^0C < t < 300^0C$* |
| T3 | *Thermal fault of medium temperature range: $300^0C < t < 700^0C$* |
| T4 | *Thermal fault of high temperature: $t > 700^0C$* |

*Table 4*

**Fault code for Dörnenburg Method [4, 5], [8]**

| Code | Fault |
|---|---|
| DP | *Partial discharge (Corona).* |
| D2 | *Discharge of high energy (arc formation).* |
| T | *Thermal fault.* |

*Table 5*

**Fault code for Duval's Triangle Method [4, 5], [8]**

| Code | Fault |
|---|---|
| DP | *Partial discharge (Corona).* |
| D1 | *Discharge of low energy.* |
| D2 | *Discharge of high energy.* |
| T1 | *Thermal fault: $t < 300^0C$* |
| T2 | *Thermal fault: $300^0C < t < 700^0C$* |
| T3 | *Thermal fault: $t < 700^0C$* |
| DT | *Discharge with arc formation and hot-spots.* |

*Table 6*

**Fault code for TDCG Method [4, 5], [8]**

| Code | Fault |
|---|---|
| N | *No fault: Normal deterioration.* |
| F1 | *Individual gases analysis. Determine load dependence.* |
| F2 | *Individual gases analysis. Plan outage.* |
| F3 | *Individual gases analysis. Consider removal from service.* |

*Table 7*

**Fault code for furan derivatives concentration [3], [12]**

| Code | Fault |
|---|---|
| H | *Moisture.* |
| P | *Pyrolysis.* |
| T | *Temperature and hot-spots.* |
| O | *Oxidation.* |

*Table 8*

**Fault code for furan derivatives concentration polymerization degree [3], [12]**

| Code | Fault |
|---|---|
| GP1 | *Degree of polymerization: 700÷1200* |
| GP2 | *Degree of polymerization: 450÷700* |
| GP3 | *Degree of polymerization: 250÷450* |
| GP4 | *Degree of polymerization: <250* |

For each analyzed method, a model was created in Fuzzy System Designer and implemented in the LabVIEW software application of the diagnosis system. The structure block diagram of every model is presented in Fig. 2. The fuzzy logic technique has helped to overcome difficulties in setting boundary conditions for gas ratios and furans, and also allows the rules to be configured in a more natural language type of structure which is more applicable and widely accepted [18-22]. For every method, the outputs of each model are divided into a set of membership functions comprising all the fault conditions which may occur in the operating transformers along with a membership function for normal conditions according to the fault codes in Tables 1-8.

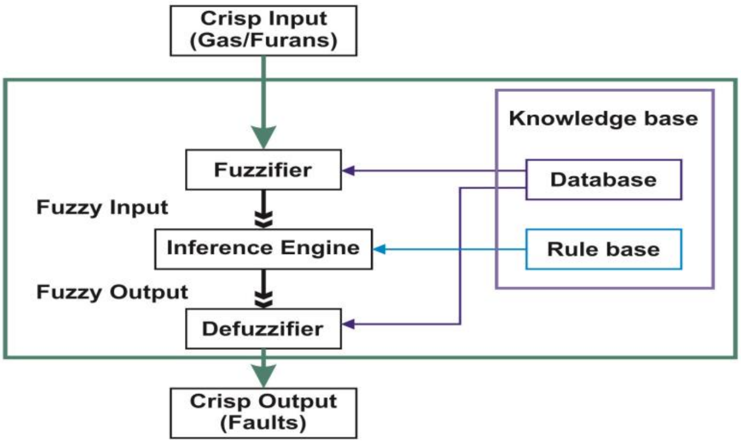


Fig. 2. Basic model structure of a fuzzy logic control system [17]

### 3.1. Fuzzification

The process of mapping from observed inputs to fuzzy sets into the various input universes of discourse is named fuzzification. In suitable linguistic terms, the mapped data are further converted as labels of the fuzzy set defined for system input variables. The degree of membership is the expected output when the variable is classified with a membership function [25].

In the proposed fuzzy diagnosis system, in Fuzzy System Designer, each crisp value of inputs is represented by trapezoid and each crisp value of outputs is represented by triangle fuzzy-membership function. For the Roger's Ratio method, the IEC Ratio method, the Dörnenburg Ratio method and Duval's Triangle method every gas ratio is defined as inputs and classified as either Low (Lo), Medium (Med) and High (Hi) according to membership intervals. For the Key Gas method and Total Dissolved Combustible Gas (TDCG) method every gas are defined as inputs and classified as either Low (Lo), Medium (Med) and High (Hi) according to membership intervals. For the analysis of furan derivatives concentration each of the five furans are defined as inputs and classified as either Low (Lo), Medium (Med) and High (Hi) according to membership intervals [17].

For example, R1 ($C_2H_2/C_2H_4$) gas ratio input for the IEC Ratio method is presented in Fig. 3 and fault output in concordance with codes from Table 2 in presented in Fig. 4.

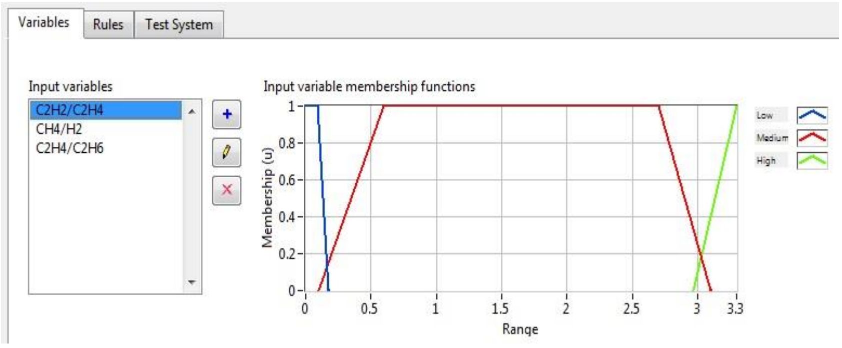


Fig. 3. R1 ratio input membership function for the IEC Ratio Method

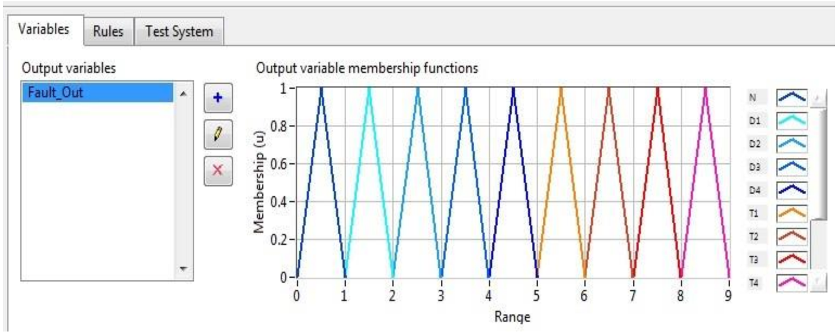


Fig. 4. Outputs membership function for the IEC Ratio Method

### 3.2. Fuzzy inference

The fuzzy rules for dissolved gas analysis methods and furan derivatives concentration analysis method have been developed based on expert's experience, modeling the operator's control actions, a fuzzy model of the process, and learning. The Mamdani-type inference, as we have defined it for the Fuzzy System Designer, expects the output membership functions to be fuzzy sets [16-18], [25]. Fig. 5 presents the set of rules for the IEC Ratio method.

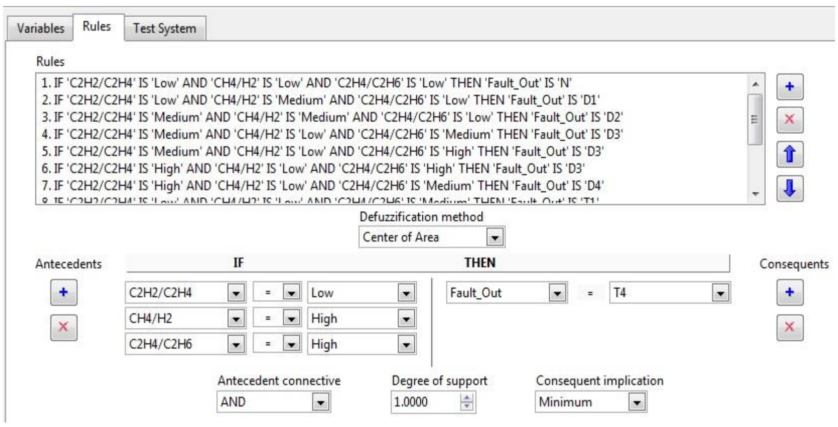


Fig. 5. Fuzzy rules for the IEC Ratio method

### 3.3. Defuzzification

The Center of Gravity method (COG) is the most popular defuzzification technique and is widely utilized in actual applications. This method is similar to the formula for calculating the center of gravity in physics. The weighted average of the membership function or the center of the gravity of the area bounded by the membership function curve is computed to be the crispest value of the fuzzy quantity [25]. Fig. 6 presents as example the surface viewer of the one fault of the IEC Ratio method.

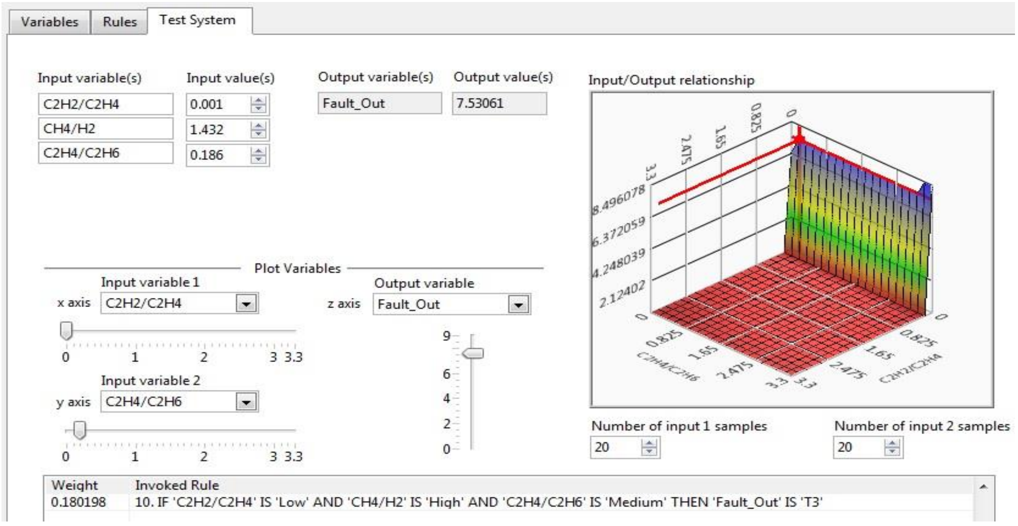


Fig. 6. Surface viewer of the one fault of the IEC Ratio method

## 4. Validation of the system diagnosis

The validation of the power transformer fault diagnosis system based on the dissolved gas analysis and furan derivatives analysis was tested on a very large number of power transformers of the Romanian Hydro-Power System. The system allows the values resulting from the laboratory dissolved gas and furan derivatives analysis to be entered into a MySQL database analysis. These are the input data for the fault diagnosis system which supply the results in automatic way.

The diagnosis fuzzy system discussed in this paper get better results by combining the most widely used methods for the dissolved gas analysis and furan derivatives analysis compared with the approach explained in [21] and obtained in [22]. For exemplification is presented in Table 9 and 10 a set of samples for dissolved gases and respectively furan derivatives from power transformers and the results and the interpretation of the diagnostic faults is achieved according to [3-5], [12].

*Table 9*

**Dissolved gas samples**

| Samples | $H_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | CO | $CO_2$ |
|---|---|---|---|---|---|---|---|
| 1. | 119 | 72 | 3 | 132 | 156 | 356 | 2849 |
| 2. | 20.70 | 58.30 | 1.70 | 25.03 | 165.03 | 210.63 | 1159.65 |
| 3. | 111 | 159 | 0.081 | 120 | 646 | 653 | 5166 |
| 4. | 61 | 120 | 0.03 | 52 | 369 | 866 | 4600 |
| 5. | 21.07 | 60.82 | 1.11 | 21.79 | 130.65 | 83.91 | 3287.68 |
| 6. | 16 | 3 | 45 | 19 | 3 | 177 | 1683 |
| 7. | 42 | 16 | 84 | 43 | 8 | 493 | 5790 |
| 8. | 34.17 | 16.70 | 46.1 | 94 | 4.51 | 306.17 | 5838.96 |
| 9. | 53 | 56 | 12 | 34 | 6.1 | 367 | 4522 |
| 10. | 28.16 | 19.96 | 38.13 | 10.2 | 3.18 | 309.08 | 4122.10 |

*Table 10*

**Furan derivatives samples**

| Samples | 2-FAL | 2-FOL | 2-ACF | 5-MEF | 5-HMF | TOTAL FURANS |
|---|---|---|---|---|---|---|
| 1. | 1.3580 | 0.0446 | 0.0344 | 0.0766 | 0.1043 | 1.6179 |
| 2. | 1.97 | 0.63 | 0.07 | 0.14 | 0.143 | 2.953 |
| 3. | 1.43 | 0.093 | 0.047 | 0.043 | 0.05 | 1.663 |
| 4. | 2.01 | 0.95 | 0.046 | 0.06 | 0.07 | 3.136 |
| 5. | 0.4671 | 0.087 | 0.1540 | 0.0863 | 0.2941 | 1.0885 |
| 6. | 0.7436 | 2.1255 | 0.0303 | 3.574 | 0.0455 | 6.5189 |
| 7. | 0.711 | 1.023 | 0.0205 | 1.021 | 0.053 | 2.8285 |
| 8. | 0.531 | 0.943 | 0.0217 | 3.341 | 0.113 | 4.9497 |
| 9. | 0.391 | 1.231 | 0.0417 | 0.453 | 0.0232 | 2.1399 |
| 10. | 0.8730 | 1.6302 | 0.1041 | 1.4792 | 0.1394 | 4.2259 |

The results of fault diagnosis system based on fuzzy logic are presented in Table 11. For the first five samples presented in Table 9 the chromatographic analyses of the dissolved gases in oil show high concentrations of certain gases, corresponding to oil and cellulosic paper breakdown processes. Thus, caution levels for carbon dioxide, methane, and ethylene are exceeded and the warning threshold is exceeded for ethane. The analysis of dissolved gas reports in interpretation of the implemented methods indicates oil and cellulose breakdown due to local heating.

*Table 11*

**Results of fault diagnosis system**

| Samples | Roger's Ratio Method | IEC Ratio Method | Dörnenburg Method | Duval Method | Key Gas Method | TDGC Method | Furan Derivatives Analysis |
|---|---|---|---|---|---|---|---|
| 1. | *T3* | *T1* | *DP* | *T3* | *T2* | *F1 Quarterly* | *O GP3* |
| 2. | *T2* | *T2* | *T* | *T2* | *T2* | *N 6 Month* | *H GP3* |
| 3. | *T2* | *T3* | *T* | *T2* | *T2* | *F1 Quarterly* | *H GP3* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4. | *T2* | *T2* | *T* | *T2* | *T2* | *F1 Quarterly* | *H GP3* |
| 5. | *T2* | *T3* | *T* | *T2* | *T3* | *N 6 Month* | *O GP2* |
| 6. | *D7* | *D3* | *D2* | *D2* | *D2 T1* | *N 6 Month* | *T GP2* |
| 7. | *D7* | *D3* | *D2* | *D2* | *D2 T1* | *N 6 Month* | *H GP2* |
| 8. | *D7* | *D3* | *DP* | *DT* | *T1* | *N 6 Month* | *T GP2* |
| 9. | *D1* | *D3* | *T* | *DT* | *T3* | *N 6 Month* | *H GP2* |
| 10. | *D4* | *D3* | *D2* | *D1* | *T1* | *N 6 Month* | *H GP2* |

The DGA interpretation performed by using the fault diagnosis system based on fuzzy logic indicates thermal failure (300°C – 700°C) with the following possible causes: faulty contacts between bolted connections, faulty connections between the cable and the bushing conductor; passing currents between the fasteners and bolts in the yokes, the fasteners and the magnetic sheets, earthing, seams or faulty clamping in the magnetic shields; damaged insulation between parallel adjacent wires in the windings [4, 5].

The CO2/CO ratio also indicates a thermal breakdown of cellulose. The presence of all five furan compounds from the first five samples form the Table 10 indicates the fact that the condition that led to the formation of these compounds is active and the paper still breaks down. The accelerated degradation of cellulose results primarily from water and oxygen contamination due to leakage as well as due to important local heating. It is noticed that the transformer in sample 4 has a high 2-FAL content which puts it in the alert area [3], [12].

For the last five samples presented in Table 9 it follows that high energy flashing occur in the transformers followed by oil breakdown by arcing between coils or between coils and earth or arcing in the on-load changer on the length of the contacts during switching with oil leaks in the main tank. It is noticed that for most of the transformers the degradation of the cellulose results from the high moisture of paper and severe local over-heating (higher concentrations of 2-FOL and 5-MEF in proportion to 2-FAL) [3], [12].

In the case of the transformer from sample 3, when the tank was removed (based on the results obtained from diagnosis system for dissolved gases and furans analysis), the following were found: the general appearance of the transformer, and the selector switch of the on-load tap changer (OLTC), is extremely dirty and with the insulation contaminated with oil derivative products and an with an appearance of ageing paper; the insulation of the flexible joints is completely damaged, resulting from the overheating of both the flexible joint and the terminal due to loose clamping nuts [4, 5].

The faults found and the conditions of the insulation confirm the result of the analysis carried out by using the fuzzy logic diagnosis system performed during the diagnostic routine. The faults have been fixed by removing the destroyed insulation, by cleaning the flexible joint and re-tightening to the corresponding torque. The selector switch of the OLTC was cleaned and the connections on the selector plots were tightened.

The fuzzy logic diagnosis system based also on the furans analysis and Pahlanvanpour's formula also makes an estimate of the degree of polymerization (See Table 11) of the solid insulation, which is very important, since the condition of the solid insulation represents the vital element in determining the life of the transformer [3, 12].

## 5. Conclusions

Starting with the fact that the current traditional methods are not consistent and they do not necessarily lead to the same conclusion for the same oil sample, we developed and test a diagnosis software system based on fuzzy logic, who consists of most widely used dissolved gas analysis methods and are making the correlation with the analysis of furan derivatives concentration for transformer faults prediction. The developed software system is open that mean it can to exchange data (data input and results) in wide range of data formats like Excel files, MySQL database and OPC client/server technology.

We can conclude that the developed system is robust and reliable intelligent system to diagnose the fault of the transformer. The results obtained from the analysis carried out using the diagnosis system were in accordance with the practical cases presented. The validation of the presented system consists in testing on a very large number of power transformers of the Romanian Hydro-Power System. The results have proven the consistency between the software decision and the expert evaluation decision. The results obtained led to the rehabilitation of the transformer and putting it into service within normal parameters.

Extensive and optimized versions of the implemented system will be approached in the future, especially in solving boundary cases using the advantages of fuzzy logic.

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