# Comparison between Fuzzy Controller and Classical Methods for Determining the Degree of Polymerization

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***Abstract* - This paper shows a fuzzy logic-based method for determining the degree of polymerization of the solid insulation of a transformer, taking into account the 2-FAL (2-furfuraldehyde) content. The proposed method generates information on the "health" condition of the transformer, with a high precision degree. The proposed system is based on two fuzzy-type controllers, and for each input/output of them it is defined a type of membership functions, triangle and trapezoid for a better response of analysis. The obtained results were compared to the results got by classical methods applied for the same 2-FAL content. For verifying the precision and accuracy, the proposed method was applied on more than a hundred of samples subjected to verification.**

**Cuvinte cheie:** *grad de polimerizare, analiza furanilor, logica fuzzy*

**Keywords:** *degree of polymerization, furan analysis, fuzzy logic.*

## I. INTRODUCTION

High power transformers are basic components in any electric power transmission or distribution network.

The demand for electricity is constantly increasing, resulting in a significant number of power transformers in operation and transformers in the process of being installed. Properly built power transformers have an average operating life of 25 to 35 years, depending on the load, temperature and maintenance. There are cases where power transformers, with proper maintenance, can reach an operating life of about 60 years [1]. There are several high-power transformers built in the 60-70s, considered to be near the end of their intended lifespan. From this perspective, studies were conducted for the development of precise and safe instruments to assess and predict the evolution of the remaining life of power transformers and to avoid the damage to the old units, with the consequences resulting from them.

Despite the continuous progress regarding the control, automation and design of power transformers, the general configuration of high power transformers, including their components and materials, remains almost unchanged from the first commercial versions.

The lifespan of transformers is determined by the lifespan of the cellulose insulation. Then, it is very important to periodically check the condition of the cellulose insulation in order to apply attenuation techniques at the right time. The most important parameter for assessing the aging condition of cellulose in transformers is its degree of polymerization (DP) [2].

For determining the DP (Degree of Polymerization) of the oil impregnated paper from an oil-filled transformer many methods were applied, such as:

- direct methods which assume disconnecting the transformer from the mains, taking insulation samples and analyzing them with a view to determining the DP by viscometric method according to IEC 60450.

- indirect methods which assume determining the DP of the cellulose insulation from the transformer, on the basis of the analysis of furan derivatives dissipated in oil, by using HPLC (High Pressure Liquid Chromatography) [3].

Indirect methods have been frequently applied for determining the aging degree.

The insulating cellulose paper may be degraded by the effect of three factors (see Fig. 1): water (hydrolysis effect) temperature (pyrolysis effect) and oxygen or oxidative agents (oxidation effect).

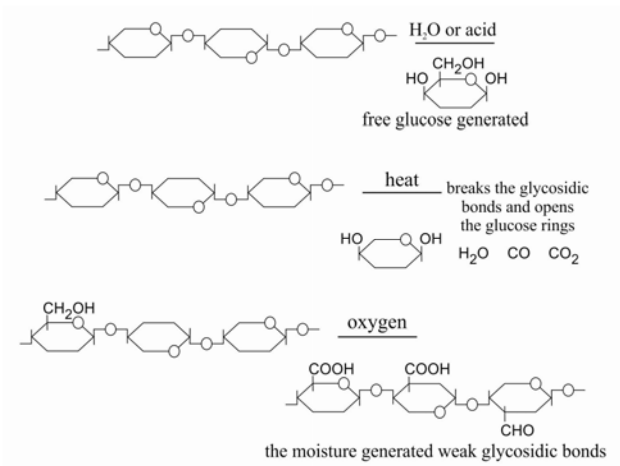



Fig. 1. The aging process

When the degradation occurs, one of the products that are forming is the family of compounds known as furans [4].

Insulating paper is composed of cellulose ~85%, hemicellulose ~15%, lignin ~8% and mineral substances ~0.8% and, consequently, all the three constituents under a degrading process may produce furan (see Fig. 2) [5]. The furan production may be also generated from pentose. The similarity between the three processes is the final product, namely 2-FAL [4], [6].

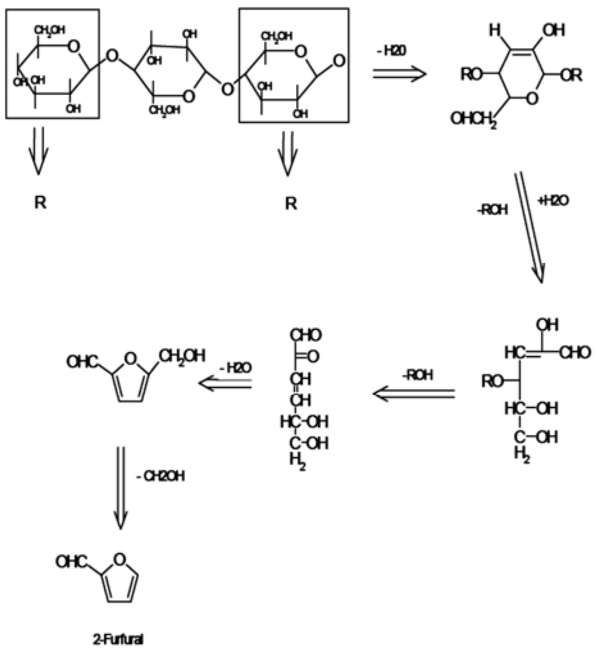
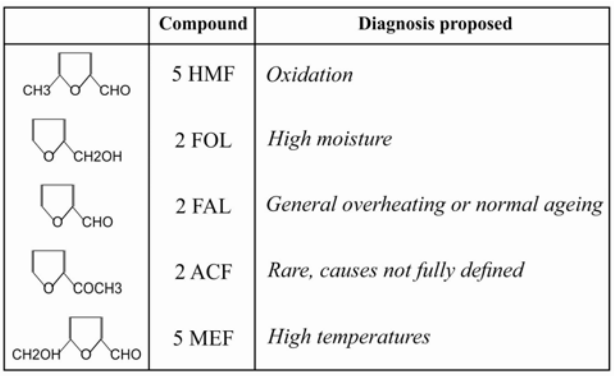



Fig. 2. Process of obtaining 2-FAL [5]

Furan compounds (see Fig. 3.) appear as a result of some concrete conditions inside the transformer, so their appearance and concentration may indicate a certain operation fault.

Some experiences were reported [7] observing changes in furanic compounds profiles over time in the presence of known conditions. According to these authors this may lead to a new and reliable way to use the other related furanic compounds. The proposed diagnosis model is presented in Fig. 3 [8].



| | Compound | Diagnosis proposed |
|---|---|---|
| CH3 O CHO | 5 HMF | *Oxidation* |
| O CH2OH | 2 FOL | *High moisture* |
| O CHO | 2 FAL | *General overheating or normal ageing* |
| O COCH3 | 2 ACF | *Rare, causes not fully defined* |
| CH2OH O CHO | 5 MEF | *High temperatures* |

Fig. 3. Possible causes of furanic compounds presence

It was found that among all the furan derivatives appearing as a result of the degradation of paper insulation, 2-FAL is the only one that was dissipated in large quantities in oil. Due to this cause and also to its thermal stability against the other derivatives, 2-FAL is the best unit of measurement for determining and monitoring the DP of the paper insulation [2], [4].

For determining the degree of polymerization of the insulation, the place where the insulation samples were taken should be also considered; there are key places in transformer winding which could generate precise information on the degradation condition of solid insulation. For this purpose, studies were developed to implement sensors in transformer windings, which allow supplying information on 2-FAL concentration [9-12]. This work completes the paper [2], emphasizing the accuracy of the methods applied in order to precise diagnoses the defects that appear in transformers.

The method for the determination of the DP of solid insulation of transformers, presented in the paper provides a faster and more accurate interpretation compared to classic methods, because the data received from the laboratory are entered into the software application, and the application processes the data and transmits the diagnostic. In addition, the proposed method is an automated method which allows the rapid diagnostic of the insulation condition, allowing the operator to take decisions in a timely manner to avoid possible damage.

## II. Classical Methods for Determining the Degree of Polymerization

Appropriately, it was found that between DP and furfuraldehydes there was a relationship. Chendong [13], Scholink [14-15], Pahlavanpour [6], [14], [16] and De Pablo [13-14] developed a series of equations for expressing the correlation between DP and 2-FAL generation. De Pablo [13-14] developed a degradation model based on experimental data and on-site measurements from a research programme performed for CIGRE (International Council of Large Electric Systems) and found that for each of the three scissions of the cellulose chain, a furfural molecule was generated [5], [17].

2-FAL is the most used furan compound for determining the degree of polymerization of the insulation, and CIGRE proposes the following interpretation of insulation condition depending on the degree of polymerization [18]:

TABLE I. Transformer Condition According to the Furan Content

| 2-FAL content | DP | Transformer condition |
|---|---|---|
| 0-0.1 | 1200-700 | Good |
| 0.1-1 | 700-450 | Moderate aging |
| 1-10 | 450-250 | High aging, risk of fault |
| >10 | < 250 | High risk of fault |

For determining the DP, the following mathematic equations relating the degree of polymerization to the 2-FAL content [5] were used:

- Chendong equation [13]:

$$DP = \frac{1.51 - \log_{10} F}{0.0035} \qquad (1)$$

- Scholinik et al. equation [14-15]

$$DP = \frac{1.17 - \log_{10} F}{0.00288} \qquad (2)$$

- Pahlavanpour equation [6], [14], [16]:

$$DP = \frac{800}{(0.186 \cdot F) + 1} \tag{3}$$

- De Pablo equation [13-14]:

$$DP = \frac{7100}{8.88 + F} \tag{4}$$

where F represents 2-FAL concentration.

## III. Fuzzy Logic Implementation

The specific of a fuzzy system consists in the fact that it may simultaneously control numerical data and lexical knowledge. It actually represents a nonlinear transformation applied to the vector of input data in a scalar output [19-22].

A fuzzy set is a set whereof nobody knows many exact things. Human expert should have the ability to get efficient reasoning even by exploiting the impreciseness, the incomplete and uncertain information. Fuzzy set theory helps to transform the qualitative human reasoning into numerical quantitative expressions. The advantage of a fuzzy set consists in the fact that there are extremely numerous possibilities leading to lots of different transformations. Intelligent systems based on fuzzy logic consider that object may belong to a set, in different degrees, flexibility in interpreting the situations being generated.

A fuzzy set is completely defined by its membership function. Most of fuzzy sets used in diverse applications have as universe of discourse the set of real numbers. For this reason, the most convenient expression of the membership function attached to a fuzzy set is that one using the analytical functions of real variable.

The triangle membership function: is defined by means of three parameters {a, b, c} as follows:

$$triangle(x;a,b,c) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-x}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0 & c \le x \end{cases} \tag{5}$$

or, by using min and max functions:

$$triangle(x;a,b,c) = \max\left\{\min\left\{\frac{x-a}{b-a}, \frac{c-x}{c-b}\right\}, 0\right\} \tag{6}$$

The trapezoid membership function: is defined by means of four parameters {a, b, c, d} as follows:

$$trapezoid(x;a,b,c) = \begin{cases} 0, & x \le a \\ \frac{x-b}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases} \tag{7}$$

or, by using the min and max functions:

$$trapezoid(x;a,b,c,d) = \\ = max\left\{min\left\{\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right\}, 0\right\} \tag{8}$$

The defuzzification methods are used for determining a real value (crisp) when its membership function is given. The most used defuzzification method is the area center method

$$x_r = C_0 A(x) = \frac{\int x \cdot \mu(x) \cdot dx}{\int \mu(x) \cdot dx} \approx \frac{\sum_i x_i \mu(x_i)}{\sum_i \mu(x_i)} \tag{9}$$

The fuzzy logic technique has helped to overcome difficulties in setting boundary conditions for furan derivatives, and also allows the rules to be configured in a more natural language type of structure which is more applicable and widely accepted.

For the implemented method, the outputs of the 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.

The process of mapping from observed inputs to fuzzy sets into the various input universes of discourse is named fuzzification. For the fuzzification, the observed data in the process control is usually in crisp set and is required to map the observed range of crisp inputs to fuzzy values corresponding to the system input variables. 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.

The proposed fuzzy analysis system presented in Fig. 4 for furan derivative 2-FAL is developed in Fuzzy System Designer, which is a tool of LabVIEW graphical programming environment. The proposed system is based on two fuzzy-type controllers, and for each input/output of them it is defined a type of membership functions, triangle and trapezoid for a better response of analysis (see Fig. 5) [23-25].

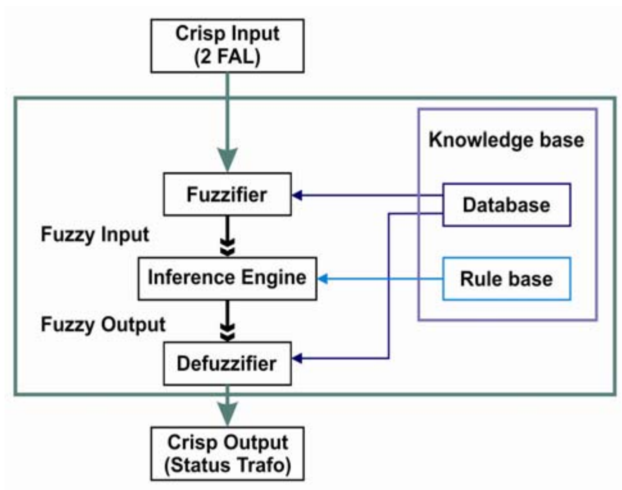



Fig. 4. Basic model structure of a fuzzy logic controller

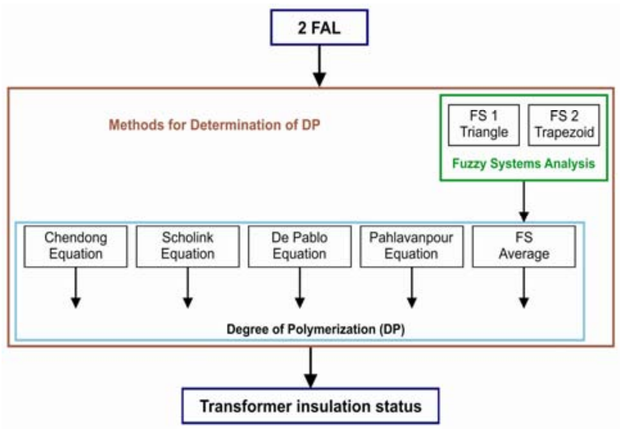



Fig. 5. Logical diagram of the method

The main sequential stages of the application program are shown in Fig. 6. In the primary data stage, the primary data provided by a specialized laboratory for the analysis of 2-FAL is automatically loaded into the application.

In the automatic extraction stage, the values loaded in the data structures specific to the LabVIEW environment are transmitted to the processing primary data stage, which implements the equations and the methodology presented in the previous stage regarding the classic determination of the degree of polymerization. Apart from these stages, the fuzzy logic processing of the 2-FAL analysis has a special role which will be presented at the end of this section.

Fig. 7, 8 and 9 present the main processing sequences of the application developed in LabVIEW regarding the concatenation of the intermediate results obtained, the decoding of the defects according to Table I and respectively, the automatic generation of a report with the results obtained after applying the classic methods and the fuzzy logic for the determination of the degree of polymerization (see Table II and Table III).

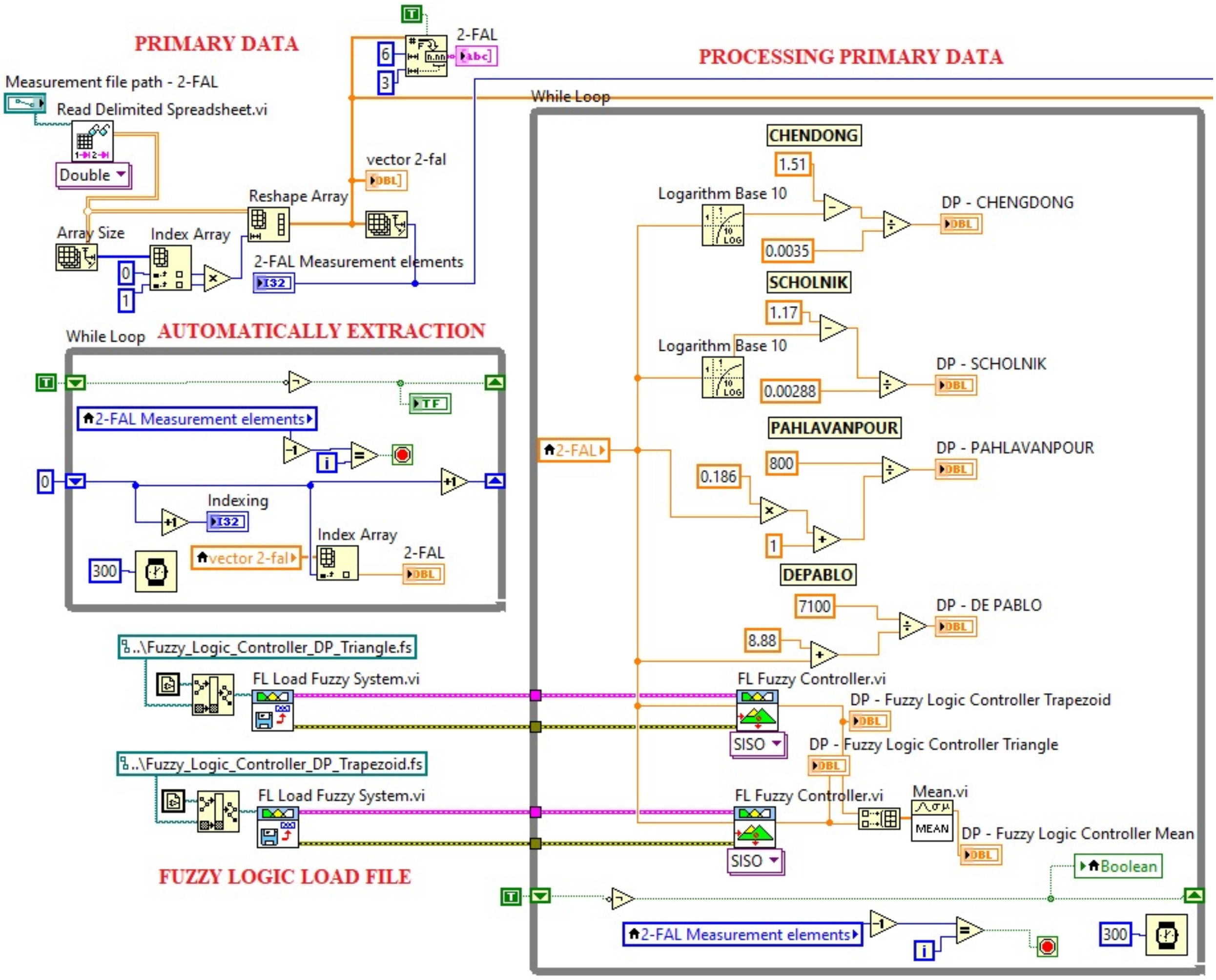



Fig. 6. The main stages of the software application program

A group of fuzzy rules, which is extracted from experts, form a fuzzy knowledge base. In constructing the fuzzy rules there are no formal standards to follow and in most applications, the fuzzy rules are expressed as “IF-THEN” style. Mamdani’s fuzzy inference method is the most commonly seen fuzzy methodology and was adopted for the fuzzy diagnosis system.

The Mamdani-type inference, as we have defined it for the Fuzzy System Designer, expects the output membership functions to be fuzzy sets.

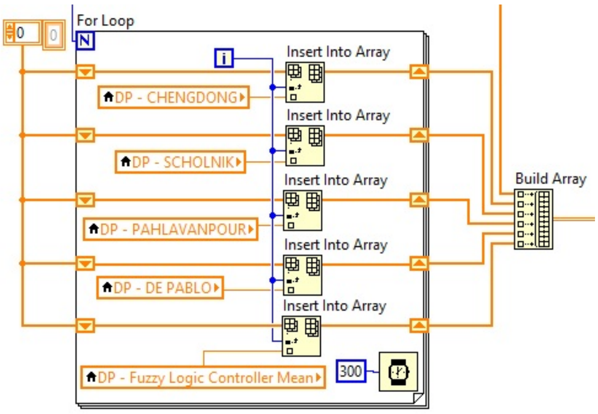



Fig. 7. Intermediate results concatenation – LabVIEW implementation

Defuzzification is used to convert the fuzzy linguistic variable to real variable and is the process of mapping from a space of inferred fuzzy control actions to a space of non-fuzzy (crisp) control actions.

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 most crisp value of the fuzzy quantity.

In Fig. 10 and 11 are presented the input and output membership functions of the fuzzy controllers, and in Fig. 12 and 13 are presented the surface viewer of the one fault of the fuzzy logic controllers.

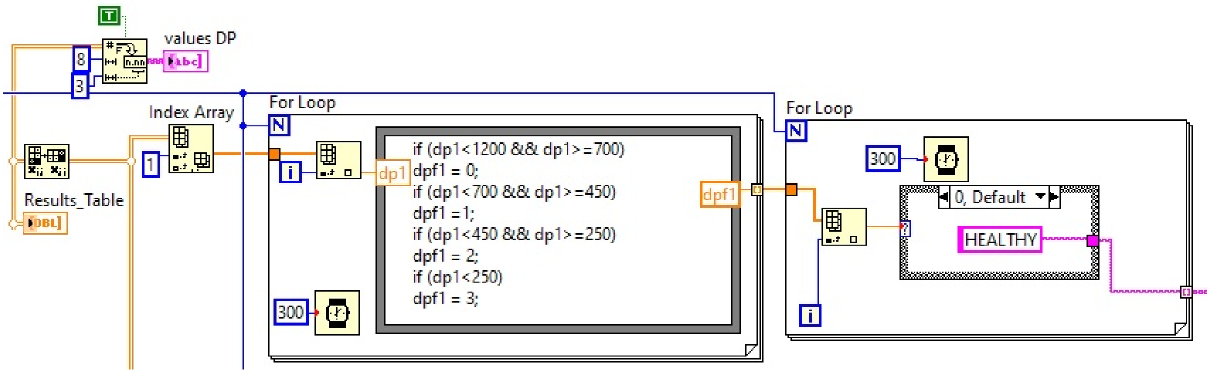



Fig. 8. Decoding faults detection – LabVIEW implementation

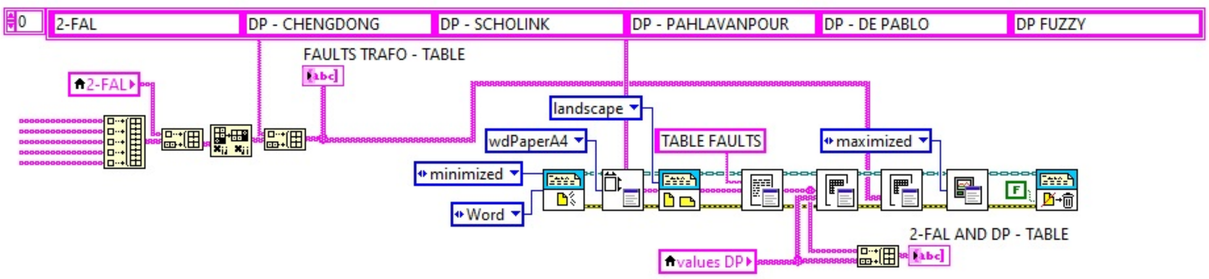



Fig. 9. Automatic reports generation – LabVIEW implementation

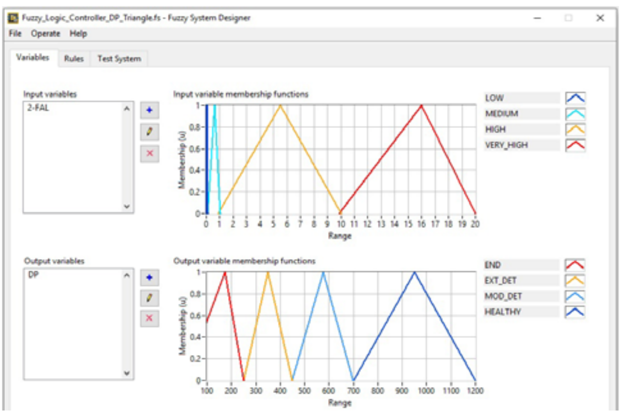



Fig. 10. Input/output triangle membership function

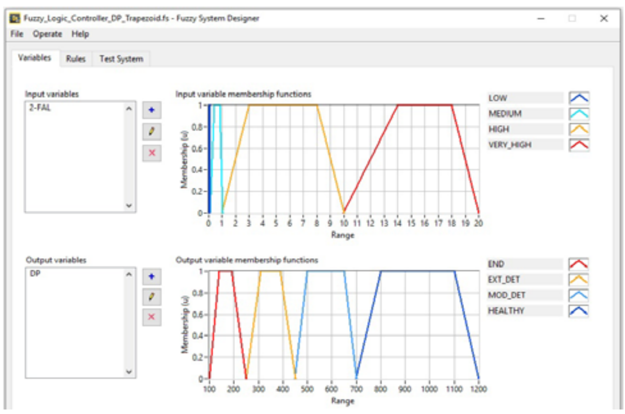



Fig. 11. Input/output trapezoid membership function

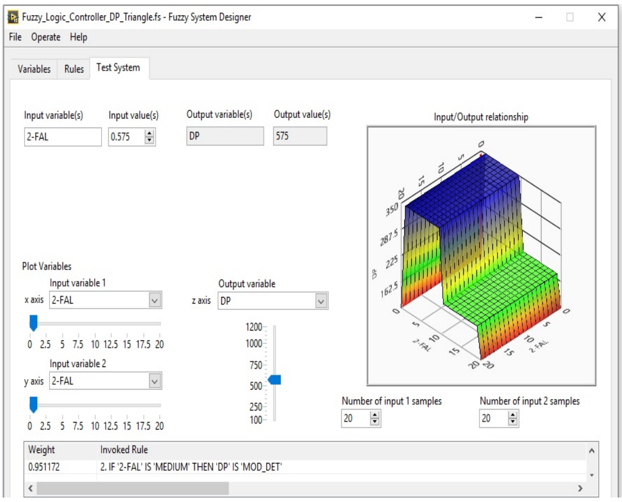



Fig. 12. Surface viewer of the one fault of the triangle fuzzy logic controller

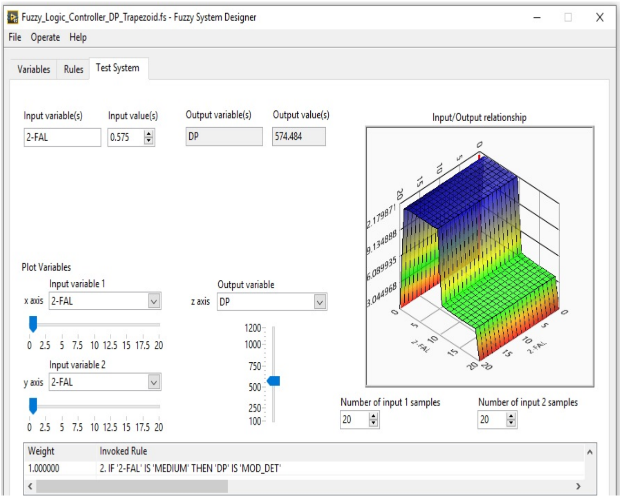



Fig. 13. Surface viewer of the one fault of the trapezoid fuzzy logic controller

It came to using the average of two fuzzy controllers, because in the first phase it was used only a controller whose inputs/outputs were defined by membership function, triangle. The results were close to those of the mathematical equations proposed by Cheondong and Scholinik, who had a decreasing trend as compared to those proposed by CIGRE (Table I).

Observing this trend, we used other fuzzy controller whose inputs/outputs were defined by membership function, trapezoid for a better response of analysis. This time, the results had an increasing trend, similar to that of the results of the mathematical equations proposed by Pahlavampur and De Pablo, exceeding the thresholds proposed by CIGRE.

For these reasons, the average between the values obtained by the two controllers was achieved, and the results were in compliance with the imposed thresholds.

To highlight this, a lot of 136 samples have been analyzed and most of them have correctly defined the condition of solid insulation of the transformers subjected to verifications.

## IV. Analysis Results

The results obtained with the Fuzzy controller are more accurate than the results obtained using mathematical equations. Both the method proposed in this paper and the classic methods comply with the thresholds proposed by CIGRE according to the 2-FAL content.

This method allows the fast interpretation of the results generated by the system developed in LabVIEW and the correct diagnostic of the health condition of the solid insulation of transformers and decision-making in a timely manner.

For demonstrating the performances of the proposed method and the data centralization mode we show an extract of 25 analyses and their interpretation in the following tables.

TABLE II. Results Obtained by Different Methods for the Degree of Polymerization

| 2-FAL | DP - CHENGDONG | DP - SCHOLINK | DP - PAHLAVANPOUR | DP - DE PABLO | DP FUZZY |
|---|---|---|---|---|---|
| 0.535 | 664.374 | 689.343 | 777.864 | 786.007 | 573.214 |
| 2.405 | 509.042 | 500.572 | 727.597 | 754.116 | 574.742 |
| 0.769 | 322.539 | 445.859 | 699.892 | 735.828 | 350.126 |
| 0.039 | 833.982 | 895.464 | 794.239 | 796.053 | 574.742 |
| 3.421 | 278.813 | 220.780 | 488.906 | 577.189 | 949.809 |
| 2.011 | 344.739 | 300.899 | 582.222 | 651.914 | 350.245 |
| 0.009 | 1015.931 | 1116.582 | 798.663 | 798.740 | 350.067 |
| 0.037 | 840.514 | 903.402 | 794.532 | 796.232 | 949.387 |
| 0.931 | 440.300 | 417.031 | 681.915 | 723.678 | 949.734 |
| 1.486 | 382.280 | 346.521 | 626.765 | 684.932 | 569.682 |
| 1.245 | 404.237 | 373.205 | 649.577 | 701.235 | 351.251 |
| 0.847 | 452.033 | 431.290 | 691.120 | 729.927 | 348.469 |
| 0.224 | 617.072 | 631.858 | 768.002 | 779.877 | 575.032 |
| 1.547 | 377.288 | 340.455 | 621.242 | 680.925 | 574.446 |
| 0.603 | 494.195 | 482.529 | 719.322 | 748.708 | 351.014 |
| 0.109 | 706.450 | 740.477 | 784.103 | 789.854 | 574.742 |
| 0.006 | 1066.242 | 1177.725 | 799.108 | 799.010 | 644.220 |
| 0.276 | 591.169 | 600.379 | 760.937 | 775.448 | 947.921 |
| 1.102 | 419.377 | 391.604 | 663.916 | 711.280 | 574.108 |
| 0.072 | 757.905 | 803.010 | 789.428 | 793.119 | 348.469 |
| 0.575 | 500.095 | 489.699 | 722.707 | 750.925 | 949.754 |
| 1.045 | 425.967 | 399.612 | 669.809 | 715.365 | 574.742 |
| 5.203 | 226.785 | 157.551 | 406.554 | 504.154 | 348.469 |
| 0.498 | 517.934 | 511.379 | 732.180 | 757.091 | 350.245 |
| 0.153 | 664.374 | 689.343 | 777.864 | 786.007 | 574.742 |

The results generated by Fuzzy controllers with a precision higher than the results obtained using mathematical equations fall within the thresholds proposed by CIGRE according to 2-FAL content. For verifying the precision and accuracy, the proposed method was applied to the 136 samples subjected to verification.

TABLE III. FAULTS INDICATED BY THE RESULTS OBTAINED BY DIFFERENT METHODS FOR THE DEGREE OF POLYMERIZATION

| 2-FAL | DP - CHENGDONG | DP - SCHOLINK | DP - PAHLAVANPOUR | DP - DE PABLO | DP FUZZY |
|---|---|---|---|---|---|
| 0.535 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | MOD_DET |
| 2.405 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | MOD_DET |
| 0.769 | EXT_DET | EXT_DET | MOD_DET | MOD_DET | EXT_DET |
| 0.039 | MOD_DET | EXT_DET | MOD_DET | HEALTHY | MOD_DET |
| 3.421 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | HEALTHY |
| 2.011 | EXT_DET | END | MOD_DET | MOD_DET | EXT_DET |
| 0.009 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | EXT_DET |
| 0.037 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | HEALTHY |
| 0.931 | EXT_DET | EXT_DET | MOD_DET | HEALTHY | HEALTHY |
| 1.486 | EXT_DET | EXT_DET | MOD_DET | MOD_DET | MOD_DET |
| 1.245 | EXT_DET | EXT_DET | MOD_DET | HEALTHY | EXT_DET |
| 0.847 | MOD_DET | EXT_DET | MOD_DET | HEALTHY | EXT_DET |
| 0.224 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | MOD_DET |
| 1.547 | EXT_DET | EXT_DET | MOD_DET | MOD_DET | MOD_DET |
| 0.603 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | EXT_DET |
| 0.109 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | MOD_DET |
| 0.006 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | MOD_DET |
| 0.276 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | HEALTHY |
| 1.102 | EXT_DET | EXT_DET | MOD_DET | HEALTHY | MOD_DET |
| 0.072 | HEALTHY | HEALTHY | HEALTHY | HEALTHY | EXT_DET |
| 0.575 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | HEALTHY |
| 1.045 | EXT_DET | EXT_DET | MOD_DET | HEALTHY | MOD_DET |
| 5.203 | END | END | EXT_DET | MOD_DET | EXT_DET |
| 0.498 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | EXT_DET |
| 0.153 | MOD_DET | MOD_DET | HEALTHY | HEALTHY | MOD_DET |

From the total of 136 analyzed samples, the following have been declared [26]:

- FN (False Negative) – samples declared incorrectly normal – only one sample,

- TP (True Positive) – samples declared precisely normal - 76 samples;

- FP (False Positive) – samples incorrectly declared normal - 6 samples

- TN (True Negative) – normal samples declared incorrectly - 53 samples.

For calculating the precision, the equation (10) is used:

$$P = \frac{TP}{TP + FP} \cong 93\% \qquad (10)$$

The method accuracy is given by the equation (11):

$$A = \frac{TP + TN}{TP + TN + FN + FP} \cong 95\% \qquad (11)$$

## V. CONCLUSIONS

The proposed fuzzy analysis system for furan derivative 2-FAL is developed in Fuzzy System Designer, which is a tool of LabVIEW graphical programming environment, and allows a rapid and exact analysis of the insulation degradation level.

The results obtained by the proposed analysis system on the basis of the furan derivative 2-FAL are precise and comply with the thresholds proposed by CIGRE as concerns the dependence between the health condition of the transformer and the 2-FAL content.

It was noticed that as regards the mathematical formula for determining the degree of polymerization implemented in the achieved programme, the results had a considerable variation, in most cases, did not comply with the levels proposed by CIGRE, had a much too positive trend although the 2-FAL concentration was high. By analyzing the results obtained both by the classic (mathematical) methods and by using the fuzzy controller presented in this paper, we conclude that the proposed method complies with the thresholds imposed by CIGRE, as opposed to the classic (mathematical) methods which have large variations and leave room for interpretation.

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Second coauthor – 25%
Third coauthor – 25%
Fourth coauthor – 25%

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## REFERENCES

[1] M. Wang, A. J. Vandermaar, K. D. Srivastava, *"Review of condition assessment of power transformers in service"*, Electr. Insul. Mag. IEEE, vol. 18, no. 6, pp. 12-25, 2002;

[2] Maria-Cristina Nițu, Ancuța-Mihaela Aciu, Claudiu-Ionel Nicola, Marcel Nicola, "Power Transformer Fault Diagnosis Using Fuzzy Logic Technique Based on Dissolved Gas Analysis and Furan Analysis", Proceedings of the Joint International Conference Optimization of Electrical & Electronic Equipment and Aegean Conference on Electrical Machines and Power Electronics (OPTIM-ACEMP), pp. 184-189, Bra□ov, Romania, 2017;

[3] Mineral insulating oils - Methods for the determination of 2-furfural and related compunds, CEI/IEC 61198, 1993;

[4] Ageing of cellulose in mineral-oil insulated transformers, Cigré brochure 323, 2007;

[5] Stavros Cristofidis, "Analytical Methods For Assessing Paper Degradation In Transformers", Master by Research, Cranfield University, 2006;

[6] B. Pahalvanpour, G. Duffy, "Rapid spectrophotometry analysis of furfuraldehyde in transformer oil", Proc. CIGRE, 1993;

[7] R. D. Stebbins, D. S. Myers, and A. B. Shkolnik, "Furanic Compounds in Dielectric Liquid Samples: Review and Update of Diagnostic Interpretation and Estimation of Insulation Age", Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials, pp. 921-926, 1-5, June 2003;

[8] Furanic Compounds for Diagnosis, Cigré brochure 494, Working Group D1.01 (TF13), 2012

[9] M. D. Manzar Nezami, Shufali Ashraf Wani, Shakeb A. Khan, Neeraj Khera, Shiraz Sohail, "An MIP-Based Novel Capacitive Sensor to Detect 2-FAL Concentration in Transformer Oil", IEEE Sensors Journal, vol.18, pp. 7924 - 7931, 2018.

[10] A. E. B. Abu-Elanien, M. M. A. Salama, M. Ibrahim, "Calculation of a health index for oil-immersed transformers rated under 69 kV using fuzzy logic", IEEE Trans. Power Del., vol. 27, no. 4, pp. 2029-2036, Oct. 2012.

[11] D. Urquiza, B. Garcia, J. C. Burgos, "Statistical study on the reference values of furanic compounds in power transformers", IEEE Electr. Insul. Mag., vol. 31, no. 4, pp. 15-23, Jul/Aug. 2015.

[12] A. Adhikary, G. Kumar, S. Banerjee, S. Sen, K. Biswas, "Modelling and performance improvement of phase-angle-based conductivity sensor", Proc. IEEE 1st Int. Conf. Control Meas. Instrum. (CMI), pp. 403-407, Jan. 2016.

[13] Chendong X., "Monitoring paper insulation ageing by measuring ageing by measuring furfural contents oil", In: EPRI, 7th Int. Symp. High Voltage Eng., pp.139-142, Dresden, Germany, 1991.

[14] A. De Pablo, "Interpretation of furanic compounds Analysis-Degradation Models", In: CIGRE WG D1.01.03.1997, Paris. France.

[15] Andrew B. Shkolnik, Robert T. Rasor, "Statistical insights into furan interpretation using a large dielectric fluid testing database", In: PES T&D 2012, pp.1-8, Orlando, FL, USA, 2012.

[16] A. De Pablo and B. Pahlavampur, "Furanic compound analysis: a tool for predictive maintenance of oil filled electrical equipment", In: CIGRE WG TF.15. 01.03.1997.

[17] J. Scheirs, G. Camino, M. Avidano, W. Tumiatti, "Origin of furanic compounds in thermal degradation of cellulosic insulating paper", J. Appl. Polym. Sci., vol. 69, pp. 2541-2547, Sep. 1998.

[18] Y. Shang, L. Yang, Z.J. Guo, Z. Yan, "Assessing aging of large transformers by furfural investigation", IEEE International Conference on Solid Dielectrics, pp. 272-274, Eindhoven, Netherlands, 2001.

[19] A. Abu-Siada, S. Hmood, and S. Islam, "A New Fuzzy Logic Approach for Consistent Interpretation of Dissolved Gas-in-Oil Analysis", IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 6, pp. 2343-2349, December 2013.

[20] R. Hooshmand, and M. Banejad, "Application of Fuzzy Logic in Fault Diagnosis in Transformers using Dissolved Gas based on Different Standards", International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, vol. 2, no. 5, 2008.

[21] H. Malik, R.K. Jarial, and H.M. Rai, "Fuzzy-Logic Applications in Transformer Diagnosis Using Individual and Total Dissolved Key Gas Concentrations," International Journal of Latest Research in Science and Technology, vol.1, no. 1, pp. 25-29, May-June 2012.

[22] N. K. Dhote, and J. B. Helonde, "Fuzzy Algorithm for Power Transformer Diagnostics," Advances in Fuzzy Systems, vol. 2013, no.6, 28 May 2013.

[23] A. Kaur, Y. S. Brar, G. Leena, "Comparative Analysis of Fault Detection in Transformers using different Fuzzy Membership Functions", IOSR Journal of Engineering (IOSRJEN), vol. 9, no. 2, February, 2019, pp. 32-37.

[24] H. P. Halvorsen. (2014, March. 07). Introduction to LabVIEW.[Online].Available: http://home.hit.no/~hansha/documents/labview/training/

[25] M. M. Nezami, S. A. Wani, S. A. Khan, N. Khera and M. A. Khan, "Fuzzy approach for residual life assessment of paper insulation", 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), Rupnagar, 2017, pp. 26-30.

[26] Joaquim P. Marques de Sá, "Applied Statistics Using SPSS, STATISTICA, MATLAB and R", Springer Berlin Heidelberg New York, 2007.

[27] Maria-Cristina Nițu, Ancuța-Mihaela Aciu, "Claudiu-Ionel Nicola, Marcel Nicola, Fuzzy Controller vs. Classical Methods for Determining the Degree of Polymerization", The 12th International Conference on Electromechanical and Power Systems - SIELMEN, 9 Octomber 2019 Craiova, 10-11 Octomber 2019 Chişinău, ISBN 978-1-7281-4011-7/19, pp. 176-181, 2019 IEEE.