An Intelligent Method for Scheduling Inspections in Transformers Based on Analysis of Combustible Gases and Physico-Chemical Parameters of the Insulating Oil

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***Abstract*— This paper presents a proposed solution using fuzzy approach, to assist the process of scheduling inspections in high power transformers (500KV), through the analysis of dissolved gases in the insulating oil, obtained using the technique of gas chromatography, and physico-chemical analysis of the oil. The development of the method was based on the criteria of gas analysis referenced standards, the statistical analysis of data and the tacit knowledge of experts. Sought to produce a solution which combines the results of traditional methods already established in the technical literature with additional situations arising from the physical-chemical analysis of the oil and the knowledge of experts, in order to increase the efficiency of such equipment inspection procedure.**

Keywords-component; Fuzzy Logic; Gas Chromatography; Physico-chemical; Factorial.

I. INTRODUCTION

The power transformers are equipments that need to be monitored by energy companies because these efforts are subject to order of thermal, electrical and mechanical, depending on the energy associated with such solicitations may imply in the formation of certain gases dissolved in mineral oil insulating directly affecting the dielectric properties of all his isolation [1].

Among existing methods of diagnosis, analysis of gas dissolved in the insulating oil is a widely used method, allowing the calculation of specific relations of rates of gas generation and the total combustible gases [2]. Currently, there are several monitoring tools in order to increase the accuracy of diagnosis [3]. Recent advances in modeling through computational intelligence techniques, software programming and more powerful processors, have permitted the functioning of numerous monitoring applications in electric power systems [4], [5], [6], [7].

In the literature there are several works that use computational intelligence techniques for diagnosing faults in transformers based on analysis of fuel gases, using the technique of gas chromatography, for example, Santos, & Vellasco [7], who have developed a Support System Decision termed for SADTRAFOS composed of a module of Computational Intelligence, which uses fuzzy rules to establish the diagnosis of the transformer through data analysis of dissolved gases, capable of offering the actions and recommendations for maintenance in accordance with the diagnosis obtained. Németh, Laboncz, Kiss, & Csépes, [6] proposed the implementation of an expert system that uses fuzzy logic combined with artificial neural networks to increasing the precision of diagnosis of faults in power transformers based on dissolved gas analysis in oil. It uses as criteria the IEEE / IEC Standard and National. These proposed solutions use a combination of these two computational techniques to aid in diagnosis of transformers, but do not include the physical and chemical factors that, in our view can contribute to an improvement in the diagnosis of potential failures in these equipments.

The proposed method uses a technique of Multivariate Analysis in the process of knowledge acquisition, and proposes a solution using fuzzy logic from traditional approaches already consolidated in the literature, with additional situations arising from the physico-chemical analysis of the oil and knowledge of experts, so as to enhance the efficiency of the inspection procedure of the equipments.

A. Statistical analysis of the data perceptive mapeamento

The case study investigated, used samples of the bottom drain of 32 different transformers 500kv substation in the Amazon region, from 2001 to 2006. In the process, we used the following concentrations in ppm (parts per million) hydrogen (H2), methane (CH4), ethylene (C2H4) and ethane (C2H6). In physicochemical analysis: color, neutralization, dielectric rigidity, power factor (PF25) and interfacial tension transformers.

The Factor Analysis (FA) is a multivariate statistical technique that has as principle analyze the structure of the interrelationships (correlations) among a large number of variables. In terms of prerequisites for application of factor analysis technique are needed some requirements, such as presence of correlations higher than 0.30, in module for the variables that are in the same factor; Barlett Sphericity test significant; appropriateness and measure of data to the model of Kaiser-Meyer-Olkin, KMO above 500 for each variable or full matrix [8], [9].

With the pre-processed data, statistical analysis was performed on the database, through factor analysis, to identify the interrelationship of simultaneous physical-chemical parameters of oil, gas and ambient conditions at the time of collection. Results identified important correlations, where the the first time specialist remarked that there is a strong relation between the gases and the physical-chemical, demonstrating that an influence on the outcome of the other. Another observation made is related the methodology used by the laboratory, where the substation is performed to analyze oil samples for diagnosis of the operating state of the power transformers in case the NBR 7274. It was found that this standard does not address all the identified outcomes. Thus, together with the expert of the area was developed a new proposal contemplating the correlations identified. The method used was principal component analysis with orthogonal rotation of the axes via Varimax. The fuzzy solution of the proposed method took into consideration the knowledge gained from factor analysis. Thus, we adopted the structure of the fuzzy system in Figure 1, where the module FUZZY 1 makes a preliminary diagnosis based on the analysis of physical-chemical parameters and the module FUZZY 2 analyzes the reasons C2H2/C2H4 concentration of gases, CH4 / H2 C2H4/C2H6, respectively represented by: R1, R2 and R3. The results obtained by the two modules, complement, strengthening the potential to hit the final diagnosis.

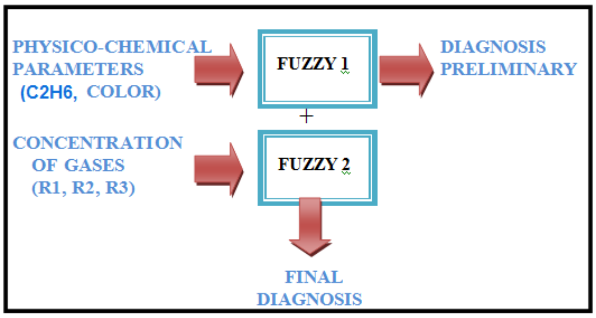


Fig. 1. Structure of the proposed fuzzy system

B. *Analysis of dissolved gases in the insulating oil.*

The analysis of gases dissolved in the insulating oil (DGA) determines the operational condition of the transformers based on the concentrations of these gases, their generation rates and the total concentration of combustible gases in the oil. Overheating, partial discharge of low energy and high energy discharge are the three primary causes associated with various types of failures. Although the analysis of dissolved gases in the insulating oil of equipment is used worldwide for over twenty years, is still regarded as the best predictive technique to diagnose internal problems in transformers. There are many methods of interpretation based DGA technique to diagnose the nature of the deterioration of the transformersuch as the criteria IEC [10], Rogers [11], Duval [12] Dornemburg [2], among others, were developed through extensive investigations of the relationships between the gases generated and the resulting incipient faults resulted..

In this work we used the method prescribed in NBR 7274, with criteria based on IEC 60599 [13].

TABLE I. DIAGNOSTICOS INDICATED BY NBR 7274

Ratio of Gases			Diagnosis	Exit
C_2H_2/C_2H_4 (R1)	**CH_4/H_2 (R2)**	**C_2H_4/C_2H_6 (R3)**		
0	0	0	Aging Normal	Normal
0	1	0	Partial discharge of low-energy	Electric Fails
1	1	0	Partial discharge of high-energy	
1 – 2	0	1 – 2	Discharge of low energy	
1	0	2	Discharge high energy	
0	0	1	Hot spot <150ºC	Thermal Fail
0	2	0	Hot spot 150º - 300ºC	
0	2	1	Hot spot 300º - 700ºC	
0	2	2	Hot spot above >700ºC	

TABLE II. LIST OF CODES NBR 7274 [6].

Ratio limits	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
	Ratio codes		
<0,1	0	1	0
>=0,1...1=<	1	0	0
>1...3=<	1	2	1
>3	2	2	2

III. RESULTS E DISCUSSION

A. *Factor Analysis*

A Factorial Analysis with varimax rotation was used to evaluate the structure of the measurement process considering the following variables: temperature (° C), humidity (%), H2, CH_4, C_2H_4, C_2H_6 and; Color, Neutralization, Dielectric rigidity, Factor Power (PF25) and Interfacial Tension. This analysis resulted in four factors, presenting 92.0% of the variance from all process (Table III).

The value of KMO (Kaiser-Meyer-Olkin Measure of Adequacy) was above .500 for the complete matrix and the Bartlett test [9], [8] was significant, indicating to be appropriate application of the technique.

TABLE III. FATOR OF MEASURING SYSTEM POWER

Variable	Commonality	Factor			
		1	2	3	4
Temperatures	0.894	0.039	-0.176	0.915	0.155
Humidity	0.991	0.094	0.114	-0.974	0.139
H_2	0.836	0.891	-0.118	0.117	-0.124
CH_4	0.967	0.968	0.093	-0.043	0.138
C_2H_4	0.939	0.958	0.026	-0.141	-0.008
Interfacial Tension	0.966	-0.083	-0.963	0.114	-0.138
Color	0.974	0.184	0.929	-0.237	0.142
Neutralization	0.963	-0.348	0.890	-0.034	0.221
Dielectric Rigidity	0.820	0.402	-0.019	0.359	-0.728
PF25	0.799	0.020	0.215	0.104	0.861
C_2H_6	0.969	0.472	0.389	0.150	0.757
% Variance		33.76	28.90	17.54	11.80
% Explained Variance		33.76	62.65	80.19	92.00

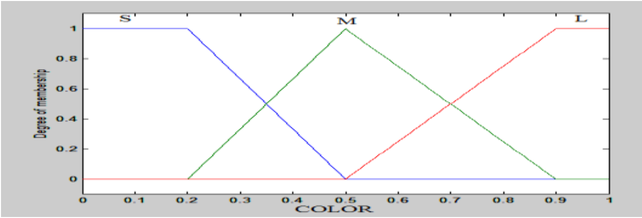
In table III, the first factor represents the gases H_2, CH_4, C_2H_4 corresponding to 33.76% of total variance, demonstrating that the formation of combustible gases are released from chemical reactions in an equivalent mannerThe second factor, accounting for 28.90% of total variance is represented by physicochemical parameters: Interfacial Tension, Color and Neutralization. Increased color corresponds to oxidation, resulting in increased acidity, the formation of polar compounds, reducing the interfacial tension.

The third factor is the temperature and humidity, corresponding to 17.54% of the total variance. The inverse correlation indicates that moisture interferes to a lesser extent at low temperatures, ie room temperature with the higher humidity decreases favoring collect the of oil. The separation of this variable on a single factor is predictable due to the sample collected no contact with the environment even though the condition of the equipment is in areas with moist atmosphere, according to ABNT NBR 7070, established per process.

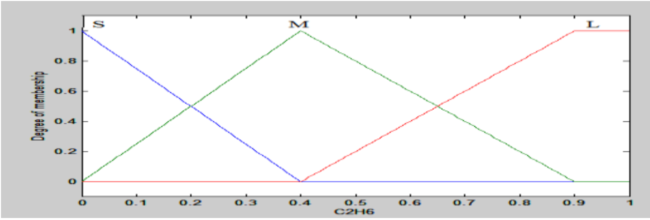
The fourth factor represents 11.8% of total variance represented by C_2H_6 gas and the physico-chemical parameters: Dielectric rigidity and Power Factor. It may be observed that the gas Ethane increases, the dielectric rigidity power factor decreases and 25 kV (PF25) increases due to polymer decomposition that occurs in the gas.

B. Fuzzy Solution Proposal

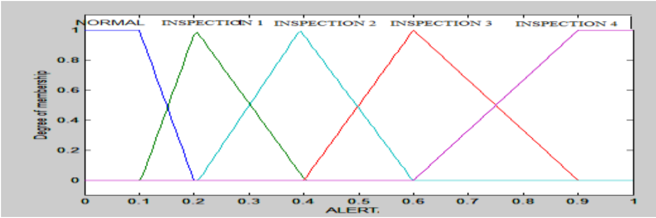
Figures 2 and 3 show the details of linguistics variables input and output modules implemented fuzzy (FUZZY 1 and FUZZY 2), with their respective universes of discourse and fuzzy sets considered. The variables considered in the solution were mapped by means of triangular and trapezoidal membership functions., based on the domains of the variables, the tacit knowledge of experts and performing some laboratory tests. In the module FUZZY 1, the input variables had their universes of discourse mapped with three fuzzy sets, SMALL (S), MEDIUM (M) LARGE (L). The ALERT output variable, Figure 2 (c), was mapped with 5 fuzzy sets (NORMAL, INSPECTION 1, INSPECTION 2, INSPECTION 3 and INSPECTION 4)



a) Color



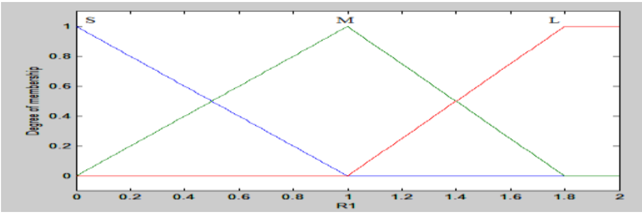
b) C2H6



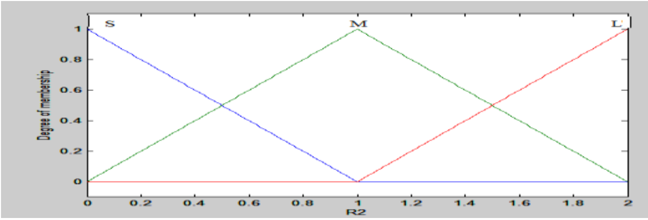
c) Alert

Fig. 2. Details of the input / output variables of FUZZY 1.

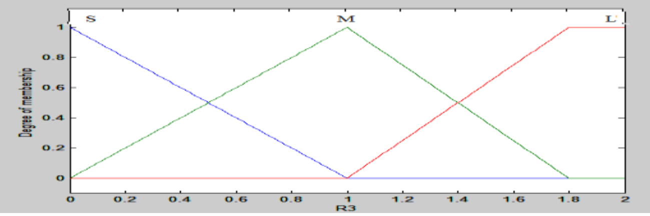
In the FUZZY module 2, the input variables are the concentration ratios of the gases C2H2/C2H4, CH4/H2, C2H4/C2H6, respectively represented by: R1, R2 and R3 and the output represented by discharging. Each input variable has been mapped for three fuzzy sets: Small (L), Medium (M) and Large (L). For each combination of input variables was possible to associate a pattern of failure as output, represented by fuzzy sets: Aging Normal (NORMAL), discharge of low energy (DBE), Discharge of high energy (DAE), thermal fault <150 º C (FTme150), thermal fault 150 º - 300 º C (FTme300), thermal fault 300 º - 700 º C (FTme700) and thermal fault> 700 º C (FTma700).



a) R1 (C2H2/C2H4)



b) R2 (CH4/H2)



d) Discharge

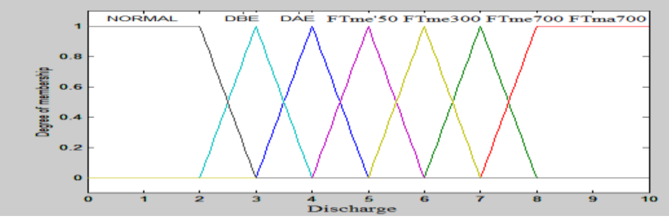


Fig. 3. Details of input / output variables of FUZZY 2

The result of factor analysis, specified in Table III, verified that if the gas Ethane (C2H6) increases, the dielectric strength decreases and power factor Kv 25 (PF25) increases could represent an additional risk for the operation of the equipment. On the other hand, the increase in color corresponds to the oxidation, with consequent increase in acidity by the formation of polar compounds decreasing the interfacial tension. Therefore combining the results of these findings with the tacit knowledge of experts, came up with the following production rules for the FUZZY module 1:

- IF COLOR IS G AND C2H6 IS G THEN INSPECTION ALERT4
- IF COLOR IS G AND C2H6 IS M THEN INSPECTION ALERT3
- IF COLOR IS G AND C2H6 IS P THEN INSPECTION ALERT2
- IF COLOR IS M AND C2H6 IS G THEN INSPECTION ALERT3
- IF COLOR IS M AND C2H6 IS M THEN INSPECTION ALERT2
- IF COLOR IS M AND C2H6 IS P THEN INSPECTION ALERT1
- IF COLOR IS P AND C2H6 IS G THEN INSPECTION ALERT3
- IF COLOR IS P AND C2H6 IS M THEN INSPECTION ALERT2
- IF COLOR IS P AND C2H6 IS P THEN NORMAL ALERT

Where the consequent rules, INSPECTION ALERT sets in ascending order gravity device status (NORMAL to INSPECAO4).

Figure 4 shows an output module 1 for values FUZZY COLOR = 0.7 ("high") and C2H6 (ethane) = 0.85 ("high"), showing how the value ALERT 0.7 or 70%, representing a real situation ALERT INSPECTION of the highest priority for the equipment, that is with this diagnosis, the technician who oversees the equipment, conclude that it is necessary to perform preventive maintenance on the equipment before it can arrive a situation of total failure.

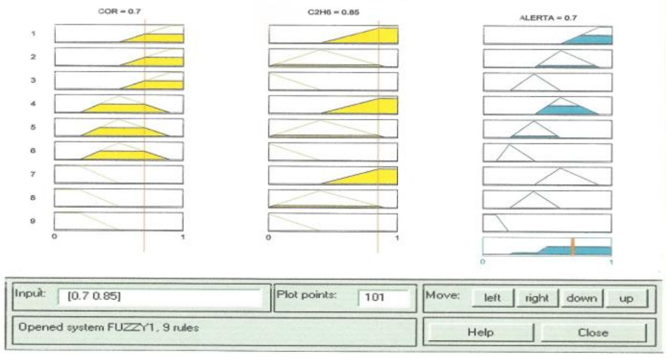


Fig. 4. Representing an output of the first module FUZZY 1

The rule base module FUZZY 2 was built from what we has to NBR 7274 and with the tacit knowledge of experts in the technique of gas chromatography, the SEP Amazon investigated, covering the some combinations not provided for by this standard, as specified in Table IV.

Example of some of the rules implemented in the module FUZZY 2:

- IF AND R1. **S** R2. **S** R3.**S** AND THEN DUMP IS **NORMAL** (Normal Aging).
- IF AND R1.**M** R2. **S** R3. **L** AND THEN DUMP IS **DAE Discharge** (high energy).
- IF AND R1.**L** R2. **S** R3.**M** AND THEN DUMP IS **DBE Discharge** (low energy

TABLE IV. LIST OF CODES NOT COVERED IN NBR7274

Ratio of Code			Diagnosis	
R1	R2	R3		
0	1	1	Discharge of low energy	S
0	1	2	Discharge of low energy	S
0	0	2	Hot spot < 150ºC	S
1	1	1	Discharge of high energy	S
1	1	2	Discharge of high energy	S
1	0	0	Discharge of low energy	S
1	2	0	Discharge of low energy	L
1	2	1	Discharge of low energy	S
1	2	2	Discharge of low energy	S
2	0	0	Discharge of low energy	L
2	2	0	Discharge of low energy	L
2	2	1	Discharge of low energy	L
2	2	2	Discharge of low energy	L

Legend:

- S: Diagnosis purchased through specialist.

- L: Diagnosis acquired through literature. These diagnoses were defined according to [9].

Figure 5 features a the module output FUZZY values for R1 = 1 (C2H2/C2H4 "medium"), R2 = 2 (CH4/H2 "high"), and R3 = 1 (C2H4/C2H6 "medium") resulting DISCHARGE how the value 3, which represents a situation Discharge Low Energy, an electrical fault.

Fig. 5. Representing an output of the module FUZZY 2

The implementation of the proposed solution used the Fuzzy Logic Toolbox ™ software Matlab. The inference machine used was the method of minimal involvement Mandani [11].

The implementation of the proposed solution used the Fuzzy Logic Toolbox ™ software Matlab. The inference engine used was the method of minimal involvement Mandani [11].

The knowledge gained through factor analysis was critical to the proposition of the solution, which incorporated a high potential of success in predictions, differentiating itself from other methods to better predict when considering the solution, the analysis of combustible gases and physico-chemical insulating oil, which tends to improvement in process efficiency.

IV. CONCLUSION

The results generated by the solution were satisfactory considering the high hit rate obtained in the validation tests. It was observed that the Fuzzy approach can be a valuable instrument for the use in solving problems in uncertain environments. The proposed solution can be adapted to any SEP, and may help the programming process inspections of high power transformers (500KV) for through the analysis of gases dissolved in the insulating oil, obtained using the technique of gas chromatography, and the analysis physicochemical oil.

Importantly, the use of Factorial Analysis in order to identify the interrelationship of simultaneous physical-chemical parameters of oil, gas and environmental conditions at the time of collection was instrumental in the acquisition of knowledge about the problem. Relations very important as it found that the ethane gas increases, the dielectric rigidity decreases and 25 Kv power factor (PF25) increases, could be confirmed.

Contemplation of physical-chemical analysis of the insulating oil aggregated considerable value to the proposal of standard diagnostics indicated by NBR 7274. Moreover, with the tacit knowledge of specialist area, we can broaden the base of rules derived from this standard technique. Thus, any SEP that performs diagnostics by NBR 7274, Will have a diagnosis which tends to be more accurate, because the new rules included in the proposal.

In the study it was found that the tools of computational intelligence can be utilized in various areas of human knowledge, with great emphasis on building solutions to problems in the field of engineering with imprecise variables.

The study showed that it is necessary to study other factors that can contribute to a better diagnosis of the operational status of power transformers, indicating that the diagnosis should not be limited only in the result of the analysis of gases dissolved in insulating oil, but consider other alternatives as physico-chemical factors which directly influence the change of state of gases in the insulating oil of transformers.

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