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Assessment of Transformer Condition using the Improve Key Gas Methods

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***Abstract*— In oil-filled transformers, the Dissolve Gas Analysis (DGA) is used as one of the well-established techniques to predict incipient faults inside its enclosure. The paper is focused on the evaluation of the transformer condition based on key gas method, suggested when there is no previous dissolved gas history, in order to prevent failure of high-voltage transformers. To increase the accuracy of the interpretation and for a better assessment of the transformer condition, a combination of fuzzy reasoning approach and the key gas method is used to improve the accuracy of the methods. The result of the prediction analyses done shows an improve of accuracy compared to the Key Gas method.**

Keywords*— Dissolved Gas Analysis (DGA); insulating materials; transformer oil; fault diagnosis

I. Introduction

The power transformers are used as interface between different voltage levels of essential importance in electrical networks. They are expensive equipments, that's why there has been a growing interest in the technique to diagnose, determine and decide the condition assessment of transformer insulation.

Over 90% of energy in Albanian Power System is produced by three main hydropower plant on the Drin River, respectively Fierza, Koman and Vau i Dejes. The HPPs are between 27 and 45 years old.

TABLE I. Main data of the concerned HPPs transformers

Power Station	River	Installed capacity (MW)	Number of Units	Rated Power (MVA)	End of first Commissioning
Vau i Dejes	Drin	250	5	60	1971
Fierza	Drin	500	4	150	1978
Koman	Drin	600	4	170	1987

In Table I are represented the data for the three main HPP's transformers, while in Fig.1are represented the years of manufacture of main transformers of Albanian TSO.

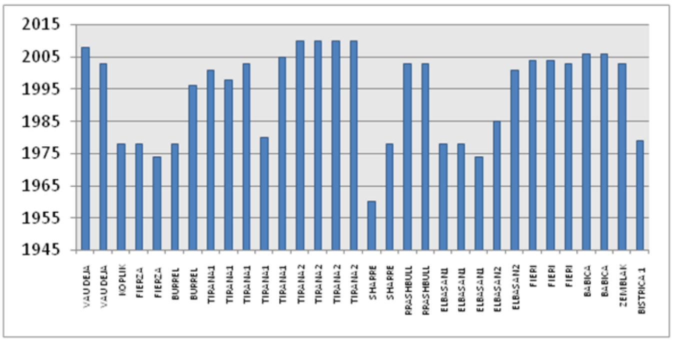


Fig. 1. The years of manufacture of main transformers of Albanian TSO

Due to the long manufacture process of step-up unit transformers, they are one of the most critical elements in term of replacement and maintenance and the monitoring becomes more popular. Monitoring systems as basis for diagnostics open the possibility for expanding the operating time, reducing the risk of expensive failures and allows several maintenance strategies.

Insulation materials degrade at higher temperatures in the presence of oxygen and moisture causing thermal stress that directly affects the electrical, chemical, and mechanical properties [1]. Diagnosing the condition of the transformer has become pertinent due to the increasing age transformers in utilities (Fig.1). Based on Dissolved Gas Analysis data [2] are calculated individual gases and TDCG concentrations with the aim to diagnose, determine and decide the condition assessment of transformers insulation.

The use of dissolved gases in insulation oils to predict the condition of power transformers started as far back as 1956 when Bucholz relay was used as fault triggers indicating the rise of certain gases that have build up in power transformer [3]. DGA is a laboratory test on oil sample taken from a transformer. The oil sample is subjected to vacuum to remove the combustible gases. These gases are then passed through a gas chromatograph and each gas is then extracted and analyzed for type and quantity [9]. The quantity of each gas is given in part per million (ppm) or percent of the total gases present in the sample. The gases are subsequently mapped out in relation with each other to generate codes used in the condition prediction. There are different DGA methods which interpret the fault in their own unique form like - Key Gas method, Roger's Ratio, IEC Ratio Method, Doernenburg Ratio Method and Duval Triangle Method, and as a result there are varying diagnostic interpretations on actual transformer conditions.

The Albanian Power Companies started to invest to DGA laboratory tests from two years, so there is no previous dissolved gas history data. In [3] it is suggested a four-level criterion to classify risks to transformers evaluating individual gas and TDCG concentrations when there is no previous dissolved gas history.

This paper is focused on the evaluation of individual gas and TDCG concentrations analysis methods. The main purpose is to defined recommendations in regard of degree on intervention in the transformers based in the conclusions of TDCG concentrations analyses to prevent failure of high-voltage transformers. To increase the accuracy of the interpretation and so increase the certainty of the transformer condition, a combination of fuzzy reasoning approach and the key gas method is used to improve the accuracy of the methods. The result of the prediction analyses done shows an improve of accuracy compared to the Key Gas method.

II. KEY GASES

The transformer is the most important equipment for power supply to consumers. Reliable power supply to consumers required proper maintenance particularly preventive maintenance. The failure in magnetic, electric and dielectric circuits as well as structural failure may cause extensive damage to the equipment and surroundings as is shown in Table II [5]. Proper operation and maintenance procedure may help to prevent failure and extend life of operation of the transformer. The gas generation and dissolved in the transformer oil are referred as key gases [2, 3]. The gases detected in the insulation oil and the fault interpretation of the transformer condition will be discussed. Power transformer gas-in-oil analysis (DGA) can be used for effective diagnostics and condition monitoring.

The principle of the Key Gas method is based on the quantity of fault gases released from the insulating oil when a fault occurs which in turn increase the temperature in the power transformer. The presence of the fault gases depends on the temperature or energy that will break the link or relation of the insulating oil chemical structure. This method uses the individual gas rather than the calculation of gas ratios for detecting fault. The significant and proportion of the gases are called "key gases". Table III lists fault gases ordered by the energy required to produce the gas in the oil, where hydrogen requires less energy and acetylene the most and the key gases that are produced when a fault occurs near the cellulose insulation.

Electrical and thermal stresses such as arching, partial discharges and overheating cause degradation of dielectric oil and solid dielectric cellulose materials. The degradation of insulation produces different gases. Important gases for fault detection include: H2, CO, CO_2, CH_4, C_2H_2, C_2H_4 and C_2H_6 [7, 8]. Different degradation mechanisms generate different gases thus making it possible to determine the degrading part of the transformer [2]. By looking at the relative proportions of gases in the DGA results it could be possible to identify the type of fault occurring in the transformer.

TABLE II. SCHEME OVER SOME POTENTIAL FAILURE MODES AND FAILURE CAUSES FOR DIFFERENT PARTS OF THE TRANSFORMER.

Component	**Component function**	**Failure mode**	**Failure causes**
Bushings	Connect windings to the network	Short circuit	External contamin. Water ingress. Sabotage.
Core	Wear magnetic field	Loss of efficiency	DC Magnetization
Solid insulation (cellulose)	Insulation of windings	Cannot supply insulation	Overload Low quality of oil
Liquid insulation (transformer oil)	Isolate and cool the active parte.	Overheated oil. Contamin. of oil.	Low oil quality Ageing Short circuits
Tank	Enclose TRAFO oil Protect the active part	Oil leakage	Corrosion Careless handling
Tap selector	Regulate the voltage level	Cannot change voltage level	Wear
Diverter switch	Maintain a coherent current	Contact failure	Contamin. of oil. Lack of maintenance.
Windings	Conduct current	Short circuit	Transient overvoltage Hot spot Movement of TRAFO
Cooling system	Cool the active part	Temperature rise	Wear

TABLE III. THE FAULT GASES

Key gas in the oil	Symbol	
Hydrogen	H2	*
Methane	CH4	*
Ethane	C2H6	*
Ethylene	C2H4	*
Acetylene	C2H2	*
Key Gas from cellulose insulation	Symbol	
Oxygen	O2	
Carbon Dioxide	CO2	
Carbon Monoxide	CO	*

* Combustible gases.

III. KEY GAS METHOD ANALYSIS

The Key Gas Method, represented in [3], is a method for determination of fault types from the gases that are typical, or predominant, at various temperatures. The method relates the key gases to different fault types by using the percentage for the combustible gases.

The Key Gas Method is mainly depends on the quantity of fault gases release in mineral oil when fault occur. Fault gases are caused by corona (partial discharge), thermal heating (pyrolysis) and arcing. The Key Gas Method considers the following four general fault types:

1. Thermal fault due to overheated oil;
2. Thermal fault due to overheated cellulose;
3. Electrical fault due to corona;
4. Electrical fault due to arcing.

The standard of IEEE Std C57.104-1991 indicates the key gases and their relative proportions for four fault types (Fig.2). Generally the thermal decomposition of oil produced more than 60% of ethylene (C_2H_2) and thermal decomposition of cellulose produce key gas carbon monoxide (CO) is 90%. In case of corona in oil mainly produce large amount principal gas hydrogen nearly 80% and due to arcing key gas acetylene produced 30% with trace quantity of hydrogen [2].

1. Thermal fault due to overheated oil

The overheated of mineral oil produced mainly methane and ethylene gases and very less quantity of ethane and hydrogen gases [4]. If the fault is severe or involves electrical contacts, small quantity of acetylene gas produced. The main Key gas is ethylene (C_2H_4). Fig.2 shows approximate relative proportions (%) for each fault gas (blue bars).

2. Thermal fault due to overheated cellulose

The overheated cellulose produced large quantity of carbon monoxide and carbon dioxide. The main key gas is carbon monoxide (CO). Fig.2 shows approximate relative proportions (%) for each fault gas. In this case CO is more than 90 %(red bars).

3. Electrical fault due to corona

Due to partial discharge (or) corona in oil are produced mainly methane and hydrogen gases with less quantity of ethylene and ethane gases. The main key gas produced due to corona in oil is hydrogen (H_2). Fig.2 shows approximate relative proportions (%) for each fault gas in corona (green bars).

4. Electrical fault due to arcing

Due to arcing (or) high energy discharge in oil produced mainly acetylene and hydrogen gases. If arcing exists in cellulose releases carbon oxides. The main key gas due to arcing is acetylene (C_2H_2). Fig. 2 shows approximate relative proportions (%) for each fault gas in arcing (yellow bars).

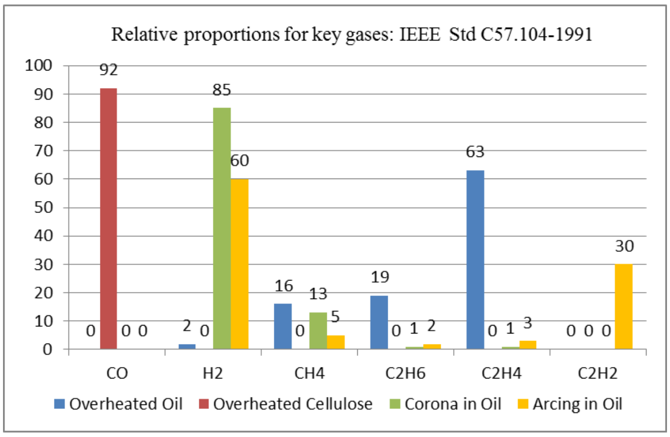


Fig. 2. Relative proportions for key gases according IEEE Std C57.104-1991

A total dissolved combustible gas (TDGC) is the definition of the sum of the combustible gas concentrations.

$$TDGC = H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2 + CO \qquad (1)$$

In [3] it is suggested a four-level criterion to classify risks to transformers when there is no previous dissolved gas history as follow:

Condition 1: TDGC below this level indicates the transformer is operating satisfactorily.

Condition 2: TDGC within this range indicates greater than normal combustible level. Action should be taken to establish a trend.

Condition 3: TDGC within this range indicates a high level of decomposition. Immediate action should be taken to establish a trend.

Condition 4: TDGC within this range indicates excessive decomposition. Continued operation could result in failure of the transformer.

If any of the individual combustible gas exceeds specified levels, further investigation should be done. Table IV lists the dissolved gas concentrations for the individual gases and TDGC for Condition 1-4. According the various levels of TDGC, in [3] is indicated the recommended initial sampling intervals and operation procedures.

TABLE IV. DISSOLVED GAS CONCENTRATIONS (PPM)

Status	H2	CH4	C2H2	C2H4	C2H6	CO	TDCG
C 1	<100	<120	<35	<50	<65	<350	<720
C 2	101-700	121-400	36-50	51-100	66-100	351-570	721-1920
C 3	701-1800	401-1000	51-80	101-200	101-150	571-1400	1921-4630
C 4	>1800	>1000	>80	>200	>150	>1400	>4630

The increasing of gas generation indicates a problem of increasing severity and there for a shorter sampling interval is recommended. These methods are mostly suitable for transformers with single fault. In case of multiple faults, only dominant fault is indicated by these methods. Further, no quantitative indication for severity of fault and maintenance suggestions is given by these methods.

IV. FUZZY LOGIC APPLICATION IN DGA KEY GAS METHODS

Although DGA has been extensively used in the industry, in some cases, the conventional methods fail to diagnose. This normally happens for those transformers which have multiple types of faults. In such a case the relation between different gases becomes too complicated that they may not match the codes pre-defined [2].To overcome these limitations, fuzzy approach is coordinate with key gas methods.

Fuzzy Logic provides an approximate but effective means of describing the behavior of systems that are too complex or not easily analyzed [3]. It differs from classical logic in that statements can take on any real value between 0 and 1, representing the degree to which an element belongs to a given set. Results obtained from [6] revealed that Fuzzy technique is a feasible approach in addressing fault classification in a transformer.

Fuzzy Logic for Key Gas Methods was developed using MATLAB to automate the evaluation of both methods. The proposed FIS Editor prepared using MATLAB Fuzzy Logic

Toolbox is shown in Fig.3. We have used the data of [11] to evaluate the method. Membership function for key gases is given in Fig.4. The fuzzy system comprises of one output showing probable mixed faults. Each output has 4 Fault type as membership functions which is shown in Fig 4. Severity is assigned to each fault type based on experienced field data.

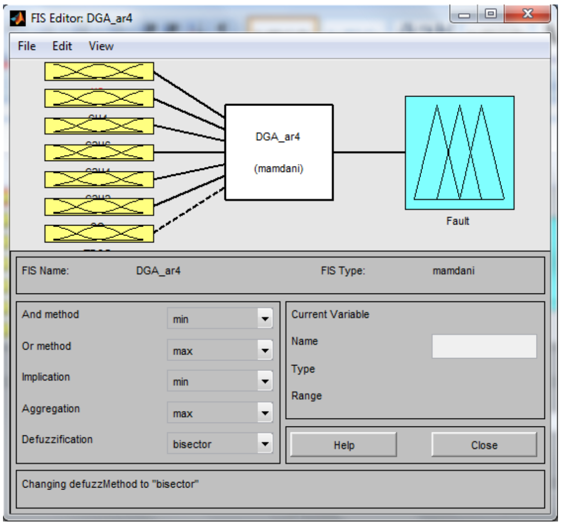


Fig. 3. Fuzzy Logic for Key gas methods using MATLAB

The first step of applying the Fuzzy Key Gas method is to determine the input and output variables by examining the relation of the key gases with the fault type. The quantization step is to define the threshold values for all the 6 input gases.

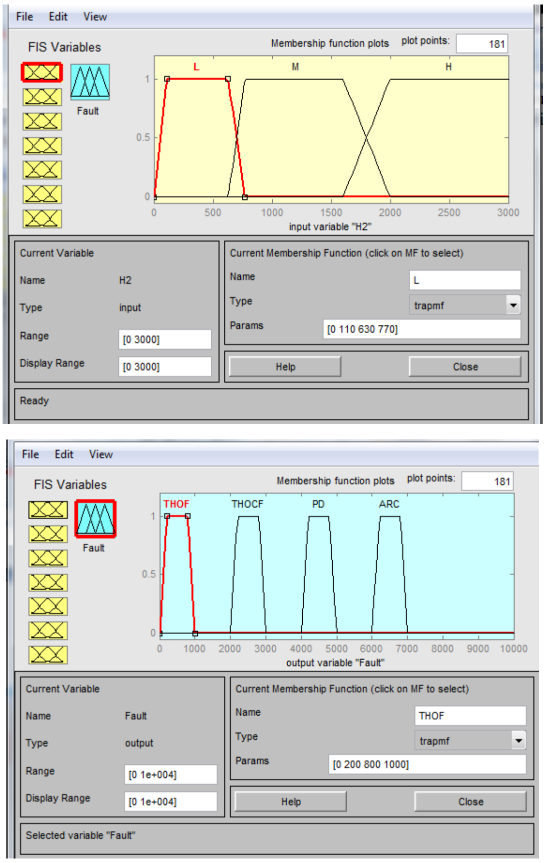


Fig. 4. Membership function for four-level criterion

Referring to the four-level criterion to classify risks to transformers (Table 4), three fuzzy codes Low, Medium and High are selected for 6 input parameter (H2, CO, C2H2, C2H4, C2H6 and CH4) to be used to determine 4 outputs. Due to uncertainty in measurements of gas concentrations by gas analyzers, 10% overlaps between two consecutive codes are apply. Membership function for codes is given by trapezoidal function (Fig.4).

In the Fuzzy Key Gas diagnostic method, we have apply first a minimum of 4 fuzzy inference rules derived from the Key Gas for single fault type based on the IEEE Standard [5] guide according IEEE Std C57.104-1991(Fig.2). The minimum fuzzy rules are shown in rule editor (Fig.5).

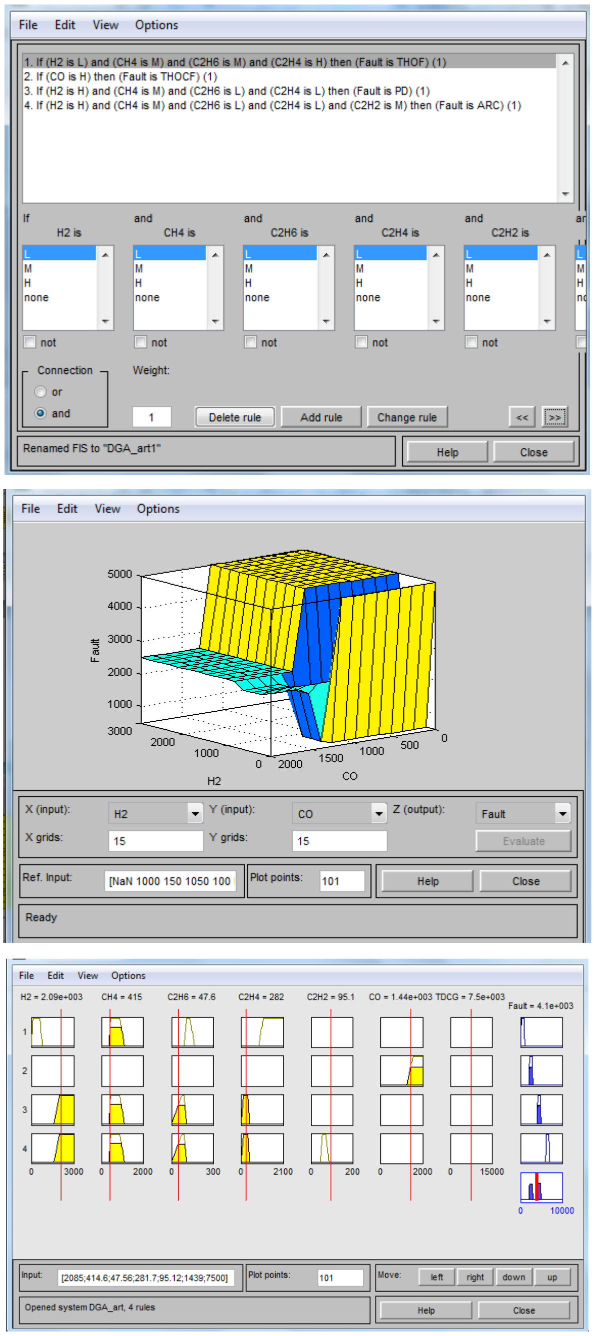


Fig. 5. The minimum Fuzzy inference rules for Fuzzy Key Gas method

Based on the IEEE Standard [5] guide, the data of Table 4 and experienced field data are suggested the 23 fuzzy inference rules for multiple faults. Each rule consists of two components, which are the antecedent (IF part), and the consequent (THEN part).With the fuzzy logic technique, the partial membership may improve the number of matched cases as compared to the ordinary crisp theory.

For the fuzzy logic control, Mamdani's Max-Min composition technique is used. FIS derives output fuzzy sets from judging all the fuzzy rules by finding the weighted average of all 23 fuzzy rules output.

In the Fuzzy Key Gas diagnostic method with 23 fuzzy inference rules we take more accurate results. The fuzzy rules for each dissolved gas are given in Fig.5, 6.

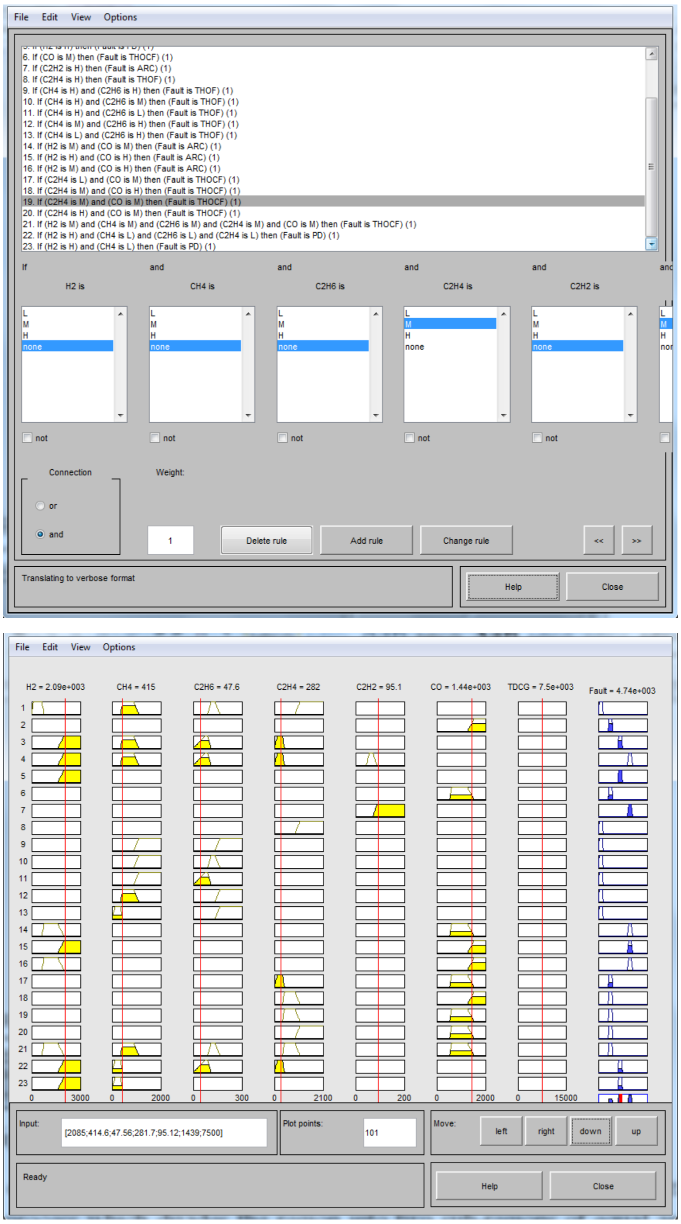


Fig. 6. Fuzzy inference rules for Fuzzy Key Gas method

In the Fuzzy Key Gas diagnostic method, we have used the Centroid and Bisector defuzzification process. The Bisector process divides the region into two sub-regions of equal area and gives more accurate results.

The result of the prediction analyses done to test the accuracy of the method using the date of [11] shows an improve of accuracy with17% compared to the individual method.

Fig.7 represents the influence of different Key Gases to the type of fault for Fuzzy Key Gas diagnostic method with 23 fuzzy inference rules used Mamdani's Max-Min composition technique.

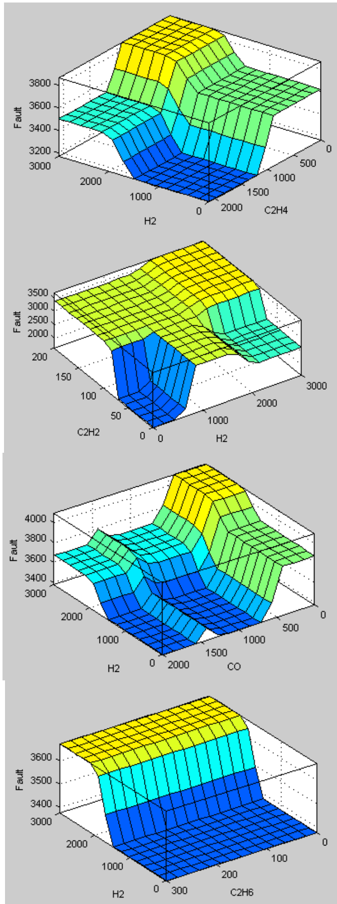


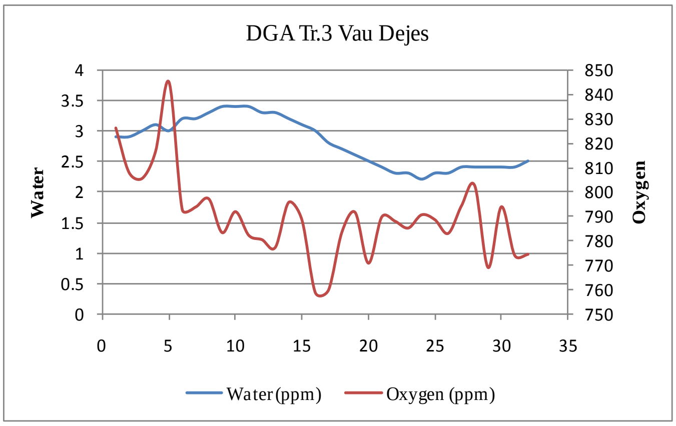
Fig. 7. The influence of different Key Gases to the type of fault for Fuzzy Key Gas diagnostic method with 23 fuzzy inference rules.

V. Case Study Main HPPs Transformers

The Albanian Power Companies started to invest in the last years to DGA on-line to monitor main HPPs transformer units, so there is a limited dissolved gas history data. The data consists of numerical measurement of each individual key gas in ppm. In Table V and Fig.8 are represented an example of the data measured for one transformer of HPP Vau Dejes.

TABLE V. DATA FROM DGA OF TRANSFORMERS OF HPP VAU DEJES

Sample date	Hydrogen (ppm)	Methane (ppm)	Acetylene (ppm)	Ethylene (ppm)	Ethane (ppm)	Carbon Monoxide (ppm)	Carbon Dioxide (ppm)	Oxygen (ppm)	TDCG (ppm)	Water (ppm)
4/9/2015 7:05	0	0.9	0.5	0.1	0.6	2.2	117	825.9	4	2.9
4/9/2015 6:05	0	1	0.3	0.1	1	2.8	106	807.6	5	2.9
4/9/2015 5:05	0	1.4	0.2	0.2	0.3	2.4	102	805.3	4	3
4/9/2015 4:05	0	1.3	0	0	0.2	2.6	110	816.5	4	3.1



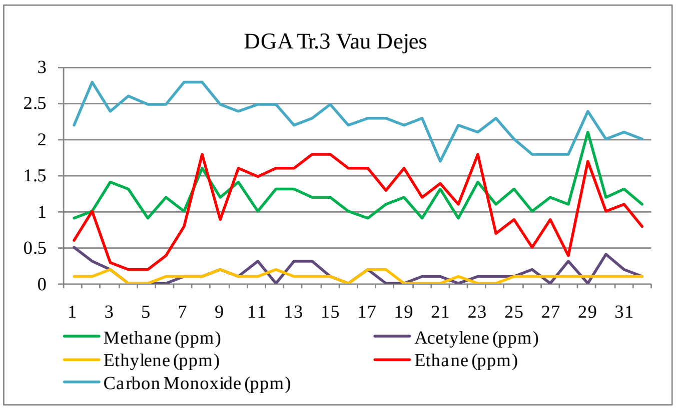


Fig. 8. The data measured for one transformer of HPP Vau Dejes.

A. *Analysis of gas data*

The data bases in this case study are DGA samples from main HPPs transformer units, measured the third Wednesday of the month during a one year period (2014).To try to identify changes in gas patterns of the transformers, the gas concentrations measured the third Wednesday of the two consecutive month are compare to have an indication of any notable sudden rise of concentrations.

In Table VI are represented 3 data samples taken to be evaluated according four-level criterion. By looking at the relative proportions of gases in the DGA results we will try to identify the type of fault occurring in the transformer, using the similarity of the histogram over the relative proportions of combustible gas.

In Table VI are shown the combustible gas measured for three transformers, while in Table VII the relative proportions of the combustible gases.

TABLE VI. THE DGA INPUT DATA OF THE THREE UNIT

No.	**H2 (ppm)**	**CH4 (ppm)**	**C2H2 (ppm)**	**C2H4 (ppm)**	**C2H6 (ppm)**	**CO (ppm)**	**TDGC (ppm)**
F3	2212	353	80	191	77	280	3193
VD4	12	75	28	415	75	307	912
F1	314	18	115	37	5	572	1061

TABLE VII. THE RELATIVE PROPORTIONS OF COMBUSTIBLE GAS OF THE THREE UNIT

No.	TDGC (ppm)	H2 %	CH4 %	C2H2 %	C2H4 %	C2H6 %	CO %
F3	3193	69.3	11.1	2.5	6.0	2.4	8.8
VD4	912	1.3	8.2	3.1	45.5	8.2	33.7
F1	1061	29.6	1.7	10.8	3.5	0.5	53.9

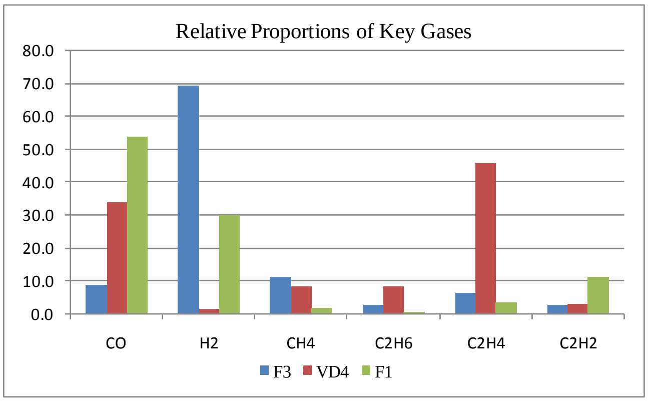
B. *Diagnosis without Fuzzy*

The histogram over the relative proportions of combustible gas of the three unit of Table VII is presented in Fig.9. Substantial increases in H_2 level in the samples suggest checking for Electrical fault due to corona or Electrical fault due to arcing. Comparing the histogram with the four general fault types one, we can see that:

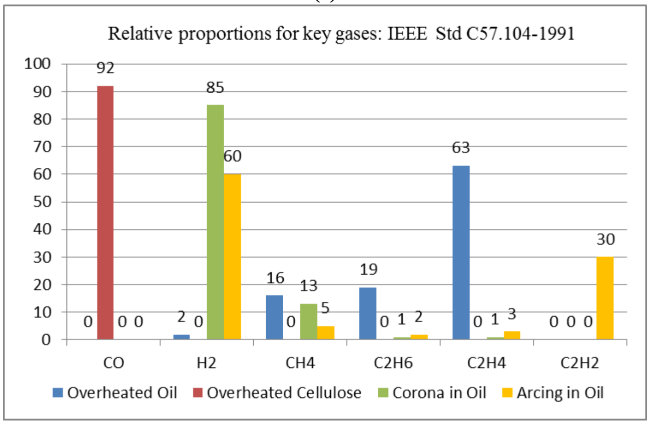
a) in case of transformer F3 (with high value of key gas H_2 and low value of key gas CH_4) it fit the histogram that indicates a corona in oil, that mean partial discharge;

b) in case of transformer VD4 (with high value of key gases CH_4 and H_2 as well as small value of CH_4 and C_2H_6) it fit the histogram that indicates overheated oil and overheated cellulose (in case of VD4 the TDGC value it is near normal);

c) in case of transformer F1 (with high value of key gases CH_4 and H_2 as well as small value of C_2H_2) it fit the histogram that indicates overheated cellulose and the possibility of arcing in oil.



(a)



(b)

Fig. 9. Histogram over the relative proportions of combustible gas (a) transformers of APC (b) IEEE standard

C. *Diagnosis with Fuzzy*

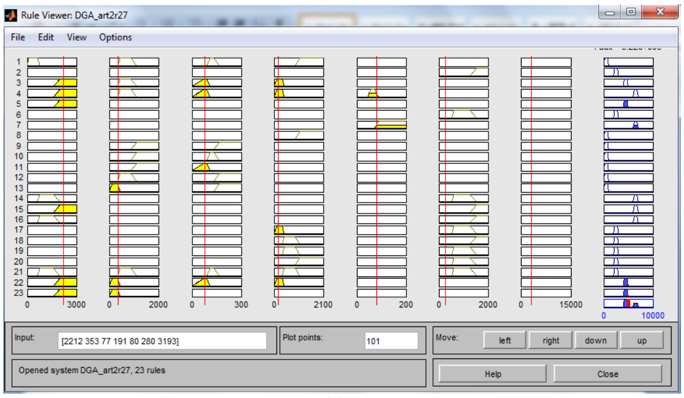
Fuzzy output is given by Rule Viewer of FIS which is shown in Fig.10. Applying the input data to the Fuzzy Key Gas diagnostic method we have found the respectively fault condition as follow:

a) in case of transformer F3, probable multiple faults are diagnosed with different belongs degrees. So, high belongs corona in oil with and mean belongs arcing are evaluated;

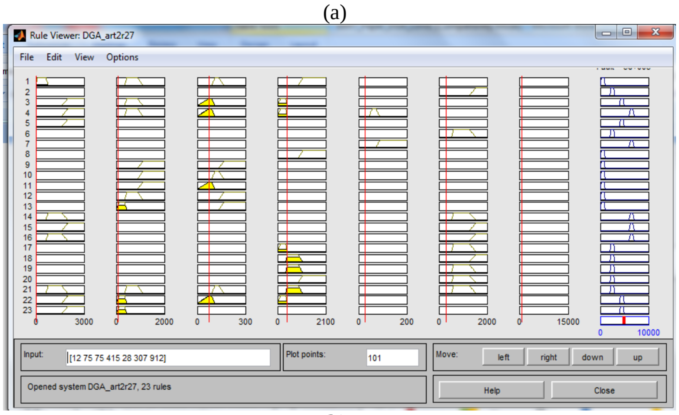
b) in case of transformer VD4 the origin of fault is unidentified. It could be explained as normal ageing factor of transformer;

c) in case of transformer F1, the thermal fault due to overheated cellulose with mean belongs is evaluated.

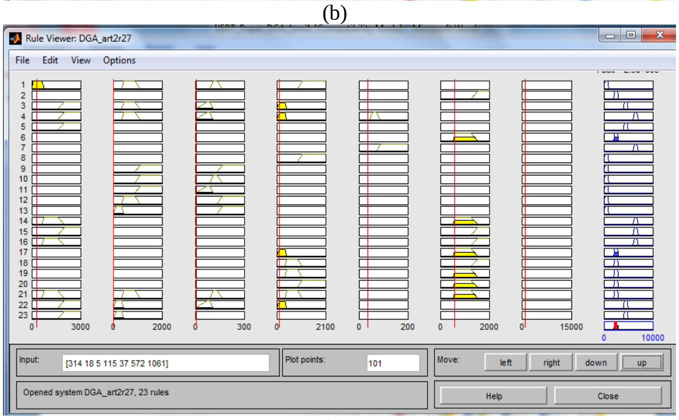
The Fuzzy representation of input-output data is shown in Table VIII.



(a)



(b)



(c)

Fig. 10. The Fuzzy Key Gas diagnostic method (a) F3 (b) VD4 (c) F1

TABLE VIII. FUZZYFICATION OF SAMPLE INPUT DATA

No.	H2	CH4	C2H2	C2H4	C2H6	CO	TDGC	Fault
F3	H	L	M	M	L	N	M	PD + ARC
VD4	N	N	L	H	N	N	L	N
F1	L	N	H	N	N	M	L	THOCF

VI. CONCLUSION

Reliable power supply to consumers required proper maintenance particularly preventive maintenance. The standards [2] and [3] are a valuable support in interpretation of DGA results, which together with further field inspections and experienced personnel judgment could give an answer what is going on inside a suspected unhealthy transformer. The Key Gas Method histogram in principal gives no answer in multiple fault condition.

To increase the accuracy of the interpretation and so increase the certainty of the assessment of the transformer condition, a combination of fuzzy reasoning and the key gas method is used to improve the accuracy of the methods.

By using Fuzzy diagnosis, number of correct predictions is increased considerably.

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