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Comparison of Conventional and Fuzzy Logic Approach for DGA of EHV Transformer

Sachin G. Gaikwad, P.S. Swami, A. G.Thosar

Abstract*— this paper deals with Dissolved gas analysis (DGA) of Extra High Voltage (EHV) transformers. Dissolved gas analysis (DGA) is a commonly used diagnostic testing tool which gives valuable information about fault developed inside the transformer. Development of incipient fault inside the transformer causes decomposition of oil and generation of combustible hydrocarbon gases. Amount and type of gas generated depends upon nature of fault in transformer.IEC and IEEE standards specify various techniques for interpretation of DGA test results. These conventional techniques include various ratio analysis methods. Many times these techniques fail to detect fault in transformer. This paper describes Fuzzy logic approach for interpretation of DGA test results. In this paper conventional and fuzzy logic method of DGA interpretation are implemented in MATLAB. DGA test data available for various EHV transformers is applied to fuzzy logic and conventional methods of DGA interpretation. Results obtained are compared with actual condition of transformer. Based on results obtained accuracy of fault detection for fuzzy logic method is calculated and compared with conventional interpretation methods.

***Index Terms*— DGA, Duval triangle, Fuzzy logic, IEC ratio..**

I. INTRODUCTION

Power transformer is costliest equipment in Extra High Voltage (EHV) substation. Premature failure of power transformer causes economic loss to power utility. Life of power transformer depends upon condition of its insulation. Power transformers are the most strategically important equipment used in power transmission system. For this reason, it is necessary to have a reliable estimation of condition of its insulation [1]. Oil forms most part of transformer insulation which also provides medium of cooling and helps to maintain transformer core and windings which are fully immersed within the oil and it also prevents direct contact with atmospheric oxygen [2]. Power transformers are always under the impact of electrical, mechanical, thermal, and environmental stresses that degrade its insulation [3]. These stresses can cause incipient faults, deterioration of insulation and even premature failure of power transformer. Transformer oil is a mineral oil which is a mixture of hydrocarbons. When transformer oil is subjected to electrical and thermal stresses, gases generated from decomposition of oil and solid insulation. In the process of degradation, gases like Methane (CH_4), Ethane (C_2H_6), Acetylene (C_2H_2), Ethylene (C_2H_4) etc. are produced along with some permanent gases like Carbon monoxide (CO), Carbon dioxide (CO_2) and Hydrogen (H_2). Decomposition of solid insulation generates Carbon monoxide (CO), Carbon dioxide (CO_2) gases [4][5]. These gases are considered as fault indicator and can be generated in certain patterns and amount depending on the characteristic of fault developed inside the transformer. The analysis of these gases provides useful information about the condition of the oil and the identification of the type of fault in the transformer. The chemical analysis of these gases is called Dissolved Gas Analysis (DGA). The DGA test requires removal of a small quantity oil sample from the transformer; this oil sample is analyzed using gas chromatography or Photo acoustic spectroscopy technique, which gives result in terms of concentration of each dissolved gas. For interpretation of DGA test results, IEC and IEEE standards suggests various gas ratio methods. These methods are conventional methods and many times they fail to detect actual fault developed in transformer. To overcome this inaccuracy of conventional methods, a fuzzy logic system is proposed for detection of fault in transformer. In this paper DGA results of 11 numbers of EHV transformers are analyzed with conventional and fuzzy logic method and results obtained are compared based on accuracy of fault detection.

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***** Correspondence Author
Sachin G. Gaikwad, ME student, Department of Electrical Engineering, Government College of Engineering Aurangabad, Aurangabad, Maharashtra State, India.
Prof. P.S. Swami, Department of Electrical Engineering, Government College of Engineering Aurangabad, Aurangabad, Maharashtra State, India.
Dr. A. G. Thosar, H.O.D., Department of Electrical Engineering, Government College of Engineering Aurangabad, Aurangabad, Maharashtra State, India.

II. CONVENTIONAL INTERPRETAION METHODS

Gas ratio analysis techniques like Roger’s ratio, IEC ratio, Basic gas ratio, Duval triangle method are suggested in standard IEC 60599 and IEEE for interpretation of DGA results.

A. Roger's ratio analysis

Roger’s method utilizes three gas ratios [6] for interpretation of DGA results. These ratios are-

$$\frac{CH_4}{H_2}, \frac{C_2H_2}{C_2H_4}, \frac{C_2H_4}{C_2H_6}$$

Depending upon values of these ratios, fault diagnosis is done using diagnosis chart as shown in Table I.

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Table I. Fault diagnosis by Roger's ratio analysis

$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_4}{C_2H_6}$	Fault diagnosis
>0.1 - <1.0	< 0.1	<1.0	Normal (No fault)
< 0.1	< 0.1	<1.0	Low-energy density discharge
0.1 – 1.0	0.1 – 3.0	>3.0	Arcing—High-energy discharge
>0.1 - <1.0	< 0.1	1.0 – 3.0	Low temperature thermal fault
>1	< 0.1	1.0 – 3.0	Thermal fault of temperature < 700 °C
>1	< 0.1	>3.0	Thermal fault of temperature > 700 °C

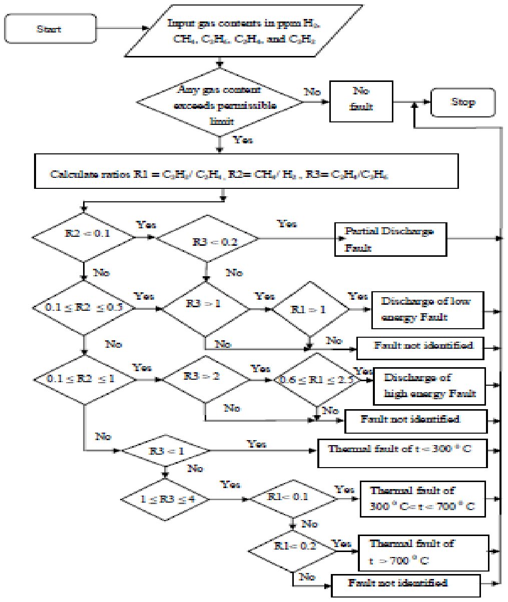

Fig.1. Flow chart of Roger's ratio method

B. IEC ratio analysis

IEC ratio analysis uses three gas ratios for fault diagnosis

$$\frac{CH_4}{H_2}, \frac{C_2H_2}{C_2H_4}, \frac{C_2H_4}{C_2H_6}$$

Diagnosis of faults is done based on ranges of the ratios as shown in Table II. Eight types of faults are detectable by this method. If combination of values of gas ratios falls out of this table, IEC ratio analysis fails to diagnose possible fault inside the transformer.

Table II. Fault diagnosis by IEC ratio analysis

$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_4}{C_2H_6}$	Fault diagnosis
0.1 – 1.0	< 0.1	<1	Normal (No fault)
<0.1	Non significant	<1	Partial discharge of low energy density
<0.1	0.1 – 3.0	<1	Partial discharge of high energy density
0.1 – 1.0	0.1 - 3.0	1.0 – 3.0	Arcing Discharge of low energy
0.1 – 1.0	>3.0	>3.0	Arcing Discharge of low energy
0.1 – 1.0	0.1 - 3.0	>3.0	Arcing Discharge of high energy
0.1 – 1.0	<0.1	1.0 – 3.0	Thermal fault of temperature less than 150 °C
>1	<0.1	<1	Thermal fault of temperature range between 150 °C to 300 °C
>1	<0.1	1.0 – 3.0	Thermal fault of temperature range 300 °C-700 °C
>1	<0.1	>3.0	Thermal fault of temperature more than 700 °C

C. Basic gas ratio analysis

IEC 60599 specifies Basic gas ratio analysis method. This method uses three gas ratios for fault interpretation-

$$\frac{C_2H_2}{C_2H_4}, \frac{CH_4}{H_2}, \frac{C_2H_4}{C_2H_6}$$

$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	Fault diagnosis
Non significant	< 0.1	< 0.2	Partial discharge
> 1	0.1- 0.5	> 1	Discharges of low energy
0.6 - 2.5	0.1 - 1	> 2	Discharges of high energy
Non significant	> 1	< 1	Thermal fault of temperature < 300 °C
< 0.1	> 1	1 - 4	Thermal fault of temperature 300 °C to 700 °C
< 0.2	> 1	> 4	Thermal fault of Temperature > 700 °C

Diagnosis chart shown in Table III is used for interpretation of possible fault in the transformer [4]-[5].

Table III. Fault diagnosis by Basic gas ratio method

Figure 2 show flow chart based on interpretation chart shown in table III.

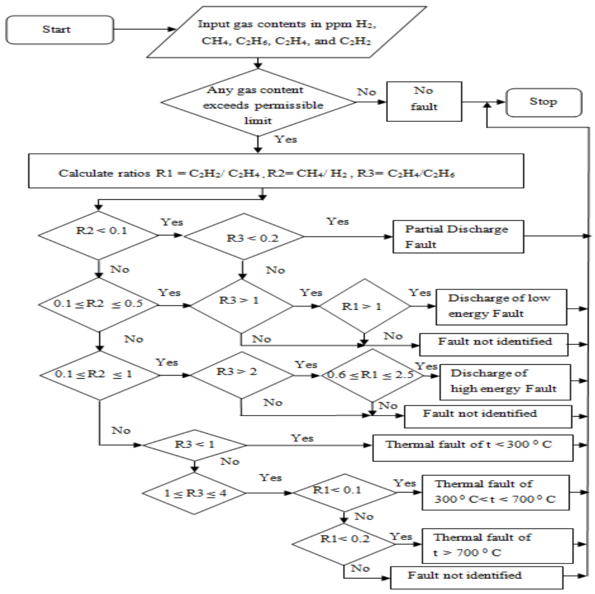

Fig.2. Flow chart of Basic gas ratio analysis

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D .Duval triangle analysis

Duval triangle method uses a triangle as shown in figure 3, having zones for different types of faults. Fault represented by each zone is shown in table IV. To obtain diagnosis, total accumulated amount of gases CH_4, C_2H_4, C_2H_2 and relative percentage of each gas is calculated as below-

$$X = C_2H_2 \ , Y = C_2H_4 \ , Z = CH_4$$

Coordinates of fault point on a Duval triangle are calculated as follows-

$$\%C_2H_2 = \frac{100X}{X+Y+Z} \ , \ \%C_2H_4 = \frac{100Y}{X+Y+Z} \ ,$$

and $\%CH_4 = \frac{100Z}{X+Y+Z}$

When a point with these coordinates is plotted over Duval triangle gives fault inside transformer.
Table IV shows fault zones in Duval triangle.

Table IV. Fault zones in Duval triangle

Fault Zone	Fault type
PD	Partial discharge
D1	Discharge of low energy
D2	Discharge of high energy
D+T	Thermal and electrical fault
T1	Thermal fault of temperature less than 300^0C
T2	Thermal fault of temperature between 300^0C to 700^0C
T3	Thermal fault of temperature more than 700^0C

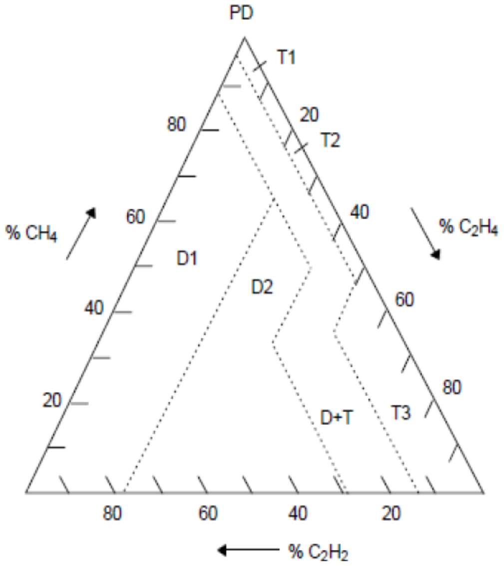

Fig.3. Duval triangle for fault analysis

III. GROUPING OF FAULT TYPES

DGA interpretation by classical methods gives different fault types for a particular DGA test result. In order to compare accuracy of each method, fault detected by these methods are required to be classified in same category. Table V shows grouping of faults detected by conventional methods into six fault type codes.

Table V. Grouping of fault type code

Analysis Method	PD	D1	D2	T1	T2	T3
Basic gas ratio	Partial discharge	Discharge of low energy	Discharge of High energy	Thermal fault of temperature <300^0C	Thermal fault of temperature between 300^0C to 700^0C	Thermal fault of temperature >700^0C
Duval triangle	1) Partial discharge 2) Mixture of thermal and electrical fault	Discharge of low energy density	Discharge of High energy	Thermal fault of temperature <300^0C	Thermal fault of temperature between 300^0C to 700^0C	Thermal fault of temperature >700^0C
Roger ratio	Low energy density arcing	Low energy density arcing	Arcing high energy discharge	Low temperature Thermal fault	Thermal fault <700^0C	Thermal fault of temperature>700^0C
IEC ratio	Partial discharge of low/high energy density	Discharge of low energy continuous sparking	Discharge of high energy	1)Thermal fault of temperature <150^0C 2)Thermal fault of temperature between 150^0C to 300^0C	Thermal fault of temperature between 300^0C to 700^0C	Thermal fault of temperature<700^0C

IV. DATA USED FOR ANALYSIS

In this paper, DGA test results of 11 number of EHV transformers are used for fault diagnosis using conventional of DGA interpretation. DGA test result data available in various substations are collected and is given in Table VI. In these 11 numbers of transformers combustible gases exceeded permissible limits. Internal inspection of transformers shown at sr.no. 3,4,5,6,7,10 and 11 in table VI was carried out to identify fault inside these transformers. For transformers shown at sr.no. 1 and 2, 220kV bushings of Y phase and R phase are failed due to thermal fault.

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For Transformers shown at sr.no.8 and 9 partial discharges measurement test was carried out at site to indentify and confirm partial discharge fault inside these transformers.

Table VI. DGA data used for interpretation by conventional methods

Sr. No.	Transformer Code	MVA Capacity	Voltage ratio	Gas Contents (ppm)							Actual Fault in Transformer
				H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO_2	CO	
1	T-01	315	400/220kV	28	93	36	38	0	3681	452	Thermal Fault – Hot spot in 220kV Bushing
2	T-02	315	400/220kV	21	72	34	46	4	3019	314	Thermal Fault – Hot spot in 220kV Bushing
3	T-03	167	400/220kV	40	15	43	29	21.5	9500	573	Partial Discharge near 400kV Bushing lead
4	T-04	167	400/220kV	1601	516	90	878	1081	3506	228	Arcing discharge in winding
5	T-05	50	132/33kV	24	231	77	1119	0	1824	162	Thermal Fault-core insulation damaged
6	T-06	50	132/33kV	372	315	53	788	78	3477	210	Arcing discharge in winding
7	T-07	50	132/33kV	1500	1552	574	5032	218	681	43	Thermal Fault-core insulation damaged
8	T-08	50	132/33kV	915	58	8	5	0	1815	236	Partial Discharge
9	T-09	50	132/33kV	564	25	5	5	0	1878	165	Partial Discharge
10	T-10	50	132/33kV	17	249	541	2005	0.4	1927	183	Thermal Fault-core insulation damaged
11	T-11	50	220/33kV	114	146	46	279	3	2631	421	Thermal Fault-core insulation damaged

V. MATLAB IMPLEMENTATION OF CONVENTIONAL INTERPRETATION METHODS

A MATLAB program is developed for implementing conventional methods of DGA interpretation. Flow charts of conventional DGA interpretation methods are developed using fault diagnosis table of each method. Using these flow charts a software program is written in M-file of MATLAB. Fault diagnosis rules of each method are implemented using if-else statements. Program for plotting Duval triangle is developed using graphical functions in MATLAB. DGA result data of table VI is applied to this MATLAB program of DGA interpretation. This MATLAB program gives result of DGA interpretation by each method and also plots Duval triangle graphically.

The output of MATLAB program for case no.2 in table VII is as given below-

MATLAB Program output-

ROGER RATIO ANALYSIS: (T2) Thermal fault of temperature less than 700 deg.C
****
IEC RATIO ANALYSIS: (T2) Thermal fault of medium temp between 300 to 700 deg. C
****
BASIC GAS RATIO ANALYSIS: (T2) Thermal Fault 300-700 deg.C
****
DUVAL TRIANGLE ANALYSIS: (T3) Thermal Fault of more than 700 deg.C type Fault
****

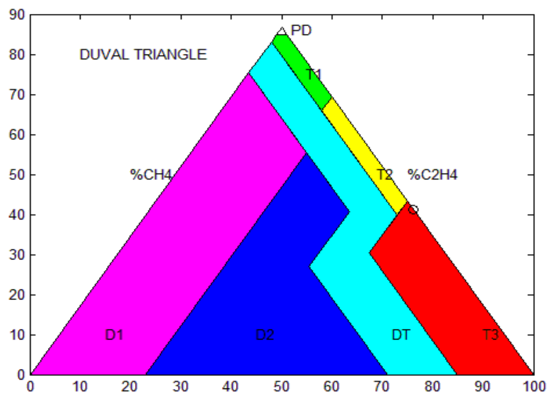

Fig.4 Duval triangle plot obtained from MATLAB program

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VI. RESULTS OF CONVENTIONAL METHODS

After applying DGA data of 11 numbers of transformers cases as shown in table VI to program of conventional methods, result shown in table VII are obtained. The results of each method are compared based on common grouped fault codes. The accuracy of conventional of DGA interpretation is calculated as follows-

Accuracy (A_T) based on total number of cases,

$$AT = 100 * \frac{Tr}{Tc} \quad (1)$$

Where, Tr = Number of correct predictions
Tc = Number of cases

By using above equation accuracy of each interpretation method for detection of possible fault inside transformer is calculated and shown in Table VIII.

Table VII. Result of Analysis by Conventional methods

Sr. No.	Transformer Code	MVA Capacity	Voltage ratio	Gas Contents (ppm)							Actual Fault in Transformer	Fault detected by conventional techniques			
				H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO_2	CO		Roger Ratio	IEC Ratio	Basic Gas Ratio	Duval Triangle
1	T-01	315	400/220kV	28	93	36	38	0	3681	452	Thermal Fault	T2	T2	T2	T2
2	T-02	315	400/220kV	21	72	34	46	4	3019	314	Thermal Fault	T2	T2	T2	T3
3	T-03	167	400/220kV	40	15	43	29	21.5	9500	573	Partial Discharge	NA	NA	T1	NA
4	T-04	167	400/220kV	1601	516	90	878	1081	3506	228	Partial Discharge	D2	D2	D1	D2
5	T-05	50	132/33kV	24	231	77	1119	0	1824	162	Thermal Fault	T3	T3	T3	T3
6	T-06	50	132/33kV	372	315	53	788	78	3477	210	Arcing Discharge	NA	NA	NA	PD
7	T-07	50	132/33kV	1500	1552	574	5032	218	681	43	Thermal Fault	T3	T3	T3	T3
8	T-08	50	132/33kV	915	58	8	5	0	1815	236	Partial Discharge	PD	PD	T1	T1
9	T-09	50	132/33kV	564	25	5	5	0	1878	165	Partial Discharge	NA	NA	NA	T1
10	T-10	50	132/33kV	17	249	541	2005	0.4	1927	183	Thermal Fault	T3	T3	T2	T3
11	T-11	50	220/33kV	114	146	46	279	3	2631	421	Thermal Fault	T3	T3	T3	T3

Table VIII. Calculated accuracy of conventional methods

	Conventional methods			
	Roger ratio	IEC ratio	Basic gas ratio	Duval triangle
Total Cases(T_C)	11	11	11	11
No predictions (T_{NP})	3	3	2	1
Correct predictions (T_R)	8	8	7	8
Accuracy (A_T)	72.72%	72.72%	63.63%	72.72%

From above results it is seen that conventional methods gives different interpretation for same DGA test result, and in some cases they failed to interpret actual condition of transformer. One shortcoming of these ratio methods is that, if gas ratio's patterns don't matches with interpretation table, conventional methods fail to detect fault .It is because of fact that, boundaries of gas ratios used in these methods are crisp boundaries. In actual situation, gas ratio boundaries are non crisp and are of fuzzy nature. As a result these gas ratios lead to errors and abrupt changes in diagnosis moving across crisp boundaries from one fault to another. To overcome limitations of ratio methods a fuzzy inference system by modifying IEC ratio method is proposed.

VII. PROPOSED FUZZY LOGIC METHOD FOR DGA

In this paper Sugeno fuzzy inference system is used for building model for DGA diagnosis. In Sugeno fuzzy inference system crisp inputs are fuzzified using membership function. Fuzzified inputs are applied to fuzzy rule base. A typical fuzzy rule in a zero-order Sugeno fuzzy model is in the form –
if **X** is **A** and **Y** is **B** then **Z**= **k**
Where **A** and **B** are fuzzy sets and **k** is crisply defined constant. When output of each rule is constant, all output membership functions are singleton spikes. The final output of the system is weighted average of all the rule output which is given as-

$$Output = \frac{\sum_{i=1}^{N} WiZi}{\sum_{i=1}^{N} Wi}$$

(2)

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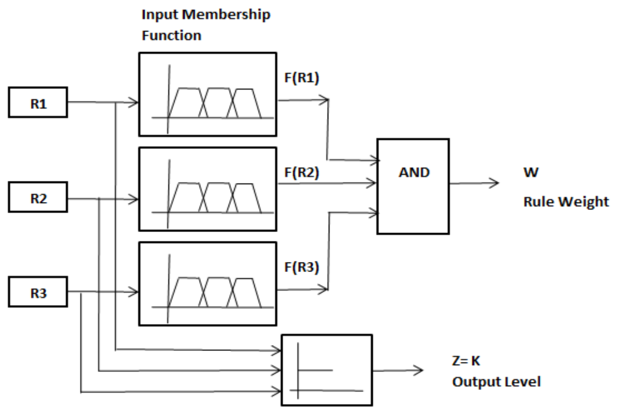

Fig.5 Sugeno model of fuzzy inference system

A suitable fuzzy logic system using Sugeno fuzzy logic model is proposed and used to analyze DGA results of EHV power transformers in shown in table VI.

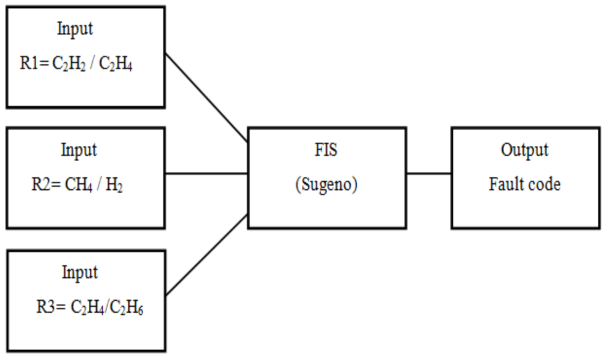

Fig.6 Proposed fuzzy inference system

Proposed model of Fuzzy Inference System (FIS) for DGA analysis is shown in Fig.6. Development of fuzzy inference system for DGA interpretation involved following processes-

A. Fuzzification of gas ratios.

In fuzzification process gas ratios are crisp inputs, each crisp value of these gas ratios is fuzzified by considering error of ± 10% as Low, Medium and High according to membership intervals defined in Table IX.

Table IX. Fuzzy ratios for membership interval

Fuzzy ratio	$R_1 = C_2H_2 / C_2H_4$	$R_2 = CH_4 / H_2$	$R_3 = C_2H_4/C_2H_6$
Low	$0.09 \leq R_1 \leq 0.11$	$0.09 \leq R_2 \leq 1.1$	$0.9 \leq R_3 \leq 1.1$
Medium	$0.09 \leq R_1 \leq 3.3$	$0.09 \leq R_2 \leq 0.11$	$0.09 \leq R_3 \leq 3.3$
High	$2.7 \geq R_1$	$0.9 \leq R_2 \leq 1.1$	$2.7 \leq R_3 \leq 3.3$

Fuzzy ratios Low, Medium and High are represented by trapezoidal membership functions for each ratio.

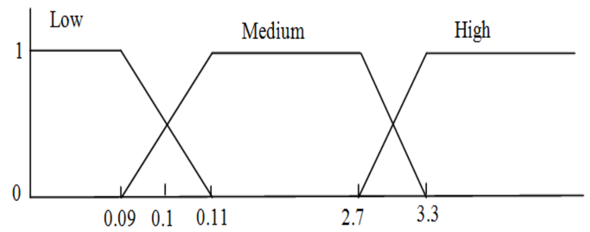

Fig.7 Membership function for C_2H_2 / C_2H_4 ratio

B. Fuzzy rule base

A fuzzy rule set consists of linguistic if-then statements, is used for deciding fault in transformer based on the fuzzy inputs. For deciding the fault in transformer 6 fault codes are defined in Table X.

Table X. Output fault code

Fault code	Fault type	Fault
0	NF	No fault
1	PD	Partial Discharge
2	D1	Discharge of low energy density continuous sparking
3	D2	Discharge of high energy density
4	T1	Overheating of temperature 150 °C to 700°C
5	T2	Overheating of temperature more than 700°C

Based on IEC ratio fault detection, following fuzzy rule base is defined

1) If **C_2H_2 / C_2H_4** is **Medium** and **CH_4 / H_2** is not **Medium** Then fault is **D2**

2) If **C_2H_2 / C_2H_4** is **High** and **CH_4 / H_2** is not **Medium** Then fault is **D2**

3) If C_2H_2 / C_2H_4 is **Medium** and **CH_4 / H_2** is **Medium** Then fault is **D1**

Like this such 8 fuzzy rules are defined.

C. Defuzzification

Output of each fuzzy rule is implicated using AND logic and then aggregated by adding all outputs of rules. Result of aggregation is defuzzified using weighted average method, which gives final output of the Sugeno type fuzzy inference system.

VIII. MATLAB IMPLEMENTATION OF FUZZY INFERENCE SYSTEM OF DGA INTERPRETATION

MATLAB software provides fuzzy logic toolbox for development of Sugeno type fuzzy inference system. By using this tool box proposed fuzzy inference system of DGA interpretation is developed. Figure 8 shows membership function for gas ratio C_2H_2 / C_2H_4, likewise trapezoidal membership functions for CH_4 / H_2 and C_2H_4/C_2H_6 gas ratios are defined.

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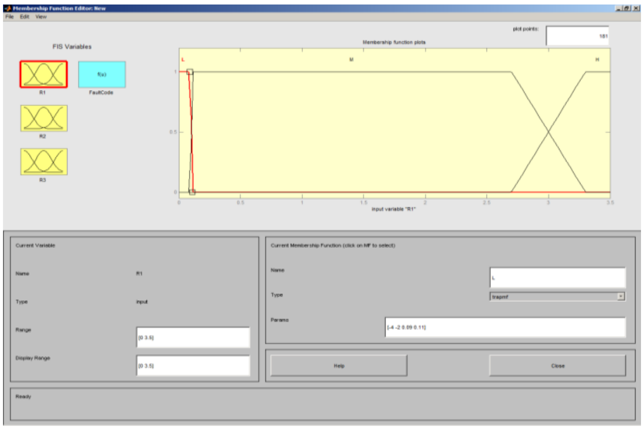

Fig.8 Membership function plot for ratio $R_1 = C_2H_2 / C_2H_4$

Output membership function have a constant value for each fault code as defined in table X. Figure 9 shows membership function for output "fault code".

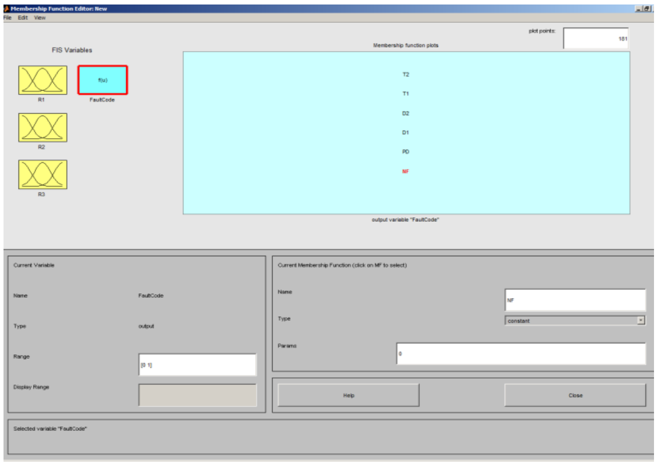

Fig.9 Membership function for output "Fault Code"

A fuzzy rule set having 8 rules defined by linguistic if-then statements is then used to form "judgment" on the fuzzy inputs derived from the three gas ratios. Output of each fuzzy rule is a constant and the solution is arrived by taking weighted average of outputs of fuzzy rules.

IX. RESULT OF FUZZY LOGIC IMPLEMENTATION

DGA results of 11 numbers of EHV transformers shown in table VI are analyzed proposed fuzzy logic method. Result of analysis is shown in table XI.

Table XI. DGA interpretation by Fuzzy logic method

Sr. No.	Transformer code	MVA Capacity	Voltage ratio	Gas Contents (ppm)							Actual Fault in Transformer	Analysis by Fuzzy Logic method
				H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO_2	CO		
1	T-01	315	400/220kV	28	93	36	38	0	3681	452	Thermal Fault	T1/T3
2	T-02	315	400/220kV	21	72	34	46	4	3019	314	Thermal Fault	T1/T3
3	T-03	167	400/220kV	40	15	43	29	21.5	9500	573	Partial Discharge	D2
4	T-04	167	400/220kV	1601	516	90	878	1081	3506	228	Partial Discharge	D2
5	T-05	50	132/33kV	24	231	77	1119	0	1824	162	Thermal Fault	T3
6	T-06	50	132/33kV	372	315	53	788	78	3477	210	Arcing Discharge	D2
7	T-07	50	132/33kV	1500	1552	574	5032	218	681	43	Thermal Fault	T3
8	T-08	50	132/33kV	915	58	8	5	0	1815	236	Partial Discharge	PD
9	T-09	50	132/33kV	564	25	5	5	0	1878	165	Partial Discharge	PD
10	T-10	50	132/33kV	17	249	541	2005	0.4	1927	183	Thermal Fault	T3
11	T-11	50	220/33kV	114	146	46	279	3	2631	421	Thermal Fault	T3

Based on results obtained in table XI, accuracy of fuzzy logic method is calculated using equation 1.

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Table XII. Calculated accuracy of Fuzzy DGA interpretation method

	Fuzzy inference system
Total Cases (T_C)	11
No predictions (T_{NP})	0
Correct predictions (T_r)	10
Accuracy (A_T)	90.90%

X. CONCLUSION

DGA test result data of EHV transformers cases are analyzed with conventional DGA interpretation techniques. It is seen that these methods many times failed to detect actual fault in transformer due to which transformers having incipient faults remained unattended. This resulted into premature failure of transformer.EHV transformer cases when analyzed with proposed Fuzzy logic method it is seen that fuzzy logic approach for DGA interpretation shown improved fault detection accuracy of 90.90% over conventional methods. Therefore fuzzy logic approach can be applied and used for analyzing DGA test results for interpretation of fault inside EHV transformers and will help to prevent premature failure of EHV transformers.

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