Integrating Fuzzy IEC Expert System based Fault Diagnosis for Power Transformer Using Dissolved Gas Analysis

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***Abstract* - The dissolved gas analysis (DGA) of transformer oil is the most used diagnosis method for power transformer faults. While various methods have been developed to interpret DGA results such as IEC gas ratio code method, and key gas method, sometimes they fail to determine the faults. In case of transformer with more than one type of fault it happens normally and in some cases, the DGA results cannot be coordinated by the existing codes making the diagnosis unproductive in multiple faults. This paper presents incorporation of intelligent fuzzy technique and IEC gas ratio code to diagnose several faults in a transformer. This revised approach is recommended for fault transformer diagnosis and the suitable actions to be taken. It has been proved to be a very advantageous tool for transformer diagnosis and upkeep planning. For instance, in fact, the gas ratio limit may not be clear, especially when more than single type of fault exist. Hence, between different types of faults, the code should not change sharply through the boundaries. The proposed method is applied to an independent data of different power transformers and various case studies of historic trends of transformer units. This method has been successfully used to identify the type of fault developing within a transformer even if there is conflict in the results of AI technique applied to DGA data.**

Index Terms - **Power transformer, DGA, Fuzzy Technique, IEC gas ratio, fault diagnosis**.

I. INTRODUCTION

The distribution part in any electrical power system characterizes 70% of all the system, whereas the main part in any distribution system is the power transformers, so the power transformers are the most important key elements in any power system [Stevenson, 1982]. Electrical and thermal stresses within a transformer result in decomposition of its insulation. Hydrolytic, oxidative and thermal degradation take place within a transformer, and these harms can direct to service outages. Due to normal aging there are some gases present within the oil; the active and incipient faults increase the gas concentrations. The DGA results of the transformer oil can be used for giving advanced caution of rising fault. Several techniques have been developed to analyze the results of the gas chromatography; such as Dornenburgs ratio method, Rogers ratio method, Key gas method of IEEE std. C57.104 [1], International Electrotechnical Commission (IEC) Method 60599 [2,3], Duvals Triangle [3], CIGRE Regulations [5], and Nomograph method. Each of these methods suffers from some or the other problems. Failure of single power transformer may cause long disruptions in supply, costly repairs and loss revenue. Several techniques both off-line (i.e. PD, transfer function, recovery voltage measurements, DP and furan analysis of cellulose insulation) and on-line (i.e. winding vibration, acoustic measurement of corona, temperature monitoring, gas in oil monitoring using Hydran and DGA) do exist to assist in condition valuation of power transformers.

Among these techniques, the dissolved gas in oil analysis technique is quite simple, non-intrusive and low-priced method. The conventional diagnostic methods are based on the ratio of gases produced from a fault or from several faults but with one of prevailing nature in a transformer [Dukarm, 1993] . Once gases from more than one fault in a transformer are collected, the relation between dissimilar gases becomes too complex which may not contest the codes predefined. Such as, the IEC codes are well-defined from certain gas ratios. When the gas ratio increases across the defined Boundaries (limits), suddenly the code changes between 0, 1 and 2**.** Actually, the gas ratio limit may not be clear (i.e. ambiguous or fuzzy), mainly when more than one type of fault exist [Zhang, 1996]. For that reason, between different types of faults, the code should not change suddenly across the margins. This paper is planned as follows: Introduction followed by dissolved gas analysis (DGA) explanation, IEC Code ratio scheme explained with its tables, Integrating Fuzzy IEC scheme structures (Fuz-IEC) has been demonstrated, results and Diagnosis Example are taken and the conclusion is made.

II. DISSOLVED GAS ANALYSIS (DGA)

Most of power transformers are full with oil that aids several purposes. The oil is a dielectric medium which acts as insulator and as heat transfer agent. The incipient faults happening in transformers give proof very early in their improvement stages through transformer oil gas analysis. By extracting the gases dissolved in the oil gas concentrations (in ppm) are obtained and by chromatography they can be separated. The gases that are usually found in the transformer insulating oil are hydrogen (H_2), carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), carbon monoxide (CO), ethane (C_2H_6), ethylene (C_2H_4), methane (CH_4) , and acetylene (C_2H_2). The atmosphere is the prominent source of N_2 and O_2, for partial discharge is the prominent source forH_2, CO_2 existence in the oil is as a result of overheated cellulose, besides being a constituent of the atmosphere, overheated cellulose and air pollution is contributed by the presence of CO, whereas over heated oil is accountable for the presence of $C_2H_6$and CH_4, C_2H_2 due to arcing in the oil and C_2H_4 is present due to overheated oil. The faults are classified into primarily three type; arcing or discharge, partial discharge (PD) or corona, and thermal heating. Very high intensity of energy dissipation occurs with arcing, less intensity of energy dissipation occurs with heating and the least intensity of energy dissipation occurs with PD.

As per IEC/IEEE method, it is possible to evaluate four conditions, i.e. discharge normal aging, partial discharge (PD) and thermal fault of several degrees of severity, using three ratios, CH_4/H_2, C_2H_2/C_2H_4, and C_2H_4/C_2H_6. Diagnosis of faults is accomplished through a simple coding scheme based on different ranges of ratios. Table 1 gives along with their range codes the range of the gas ratios used by IEC/IEEE method. The formation of CO_2 and CO in the oil and impregnated paper insulation increases rapidly with the increase of temperature. If the CO_2/CO ratio is <3, then it is an indication of a possible paper contribution in the fault, with specific degree of carbonization.

III. IEC GAS RATIO CODE

Even a few ppm of C_2H_2 gives the indication of high energy arcing. Trace volume of this gas can be produced by a very hot thermal fault (500 C). One time arc can produce C_2H_2; incase C_2H_2 is found frequency sampling should be done and if additional C_2H_2 is found at that time it is an indication of active arcing. The problem of increasing severity is indicated by the increasing generation rate (ppm/day).

In dissolved gas analysis, the IEC codes (International Electric Committee) have been used for quite a few decades and significant experience gathered throughout the world to diagnose emerging faults in transformers [Rogers, 1978; Senior *et al.*, 2000]. Early interpretations were focused on specific gas components such as methane and hydrogen for the determining the discharges in the oil. The ratios of certain gases, establishes more comprehensive diagnostic techniques [Haupert*et al.*, 1989,Jakob, 1989]. IEC in 1978 in "Guide for Interpretation of the Analysis of Gases in Transformer and Other Oil Filled Electrical Equipment in Service" standardized these techniques. The individual gases used to find each ratio and its allotted limits are shown in Tables (1) and (2**).** Codes are then assigned according to the value found for each ratio and the equivalent fault characterized [Rogers, 1978; Senior *et al.*, 2000].

Table 1. IEC Ratio Codes

Gas Ratios	Range of Gas ratio	Range code/IEC Code
C2H2/C2H4	<0.1	0
	0.1–1.0	1
	1.0–3.0	1
	>3.0	2
CH_4/H_2	<0.1	1
	0.1–1.0	0
	1.0–3.0	2
	>3.0	2
C 2H4/C2H6	<0.1	0
	0.1–1.0	0
	1.0–3.0	1
	>3.0	2

Table. 2 Fault classifications according to the IEC Codes

Fault type	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	INDEX
No Fault	0	0	0	F0
Partial discharges of low energy density	0	1	0	F1
Partial discharges of high energy density	1	1	0	F2
Discharges of low energy	1or 2	0	1or 2	F3
Discharges of high energy	1	0	2	F4
Thermal Fault of low temperature <150^{0}C	0	0	1	F5
Thermal Fault of low temperatures 150-300 ^{0}C	0	2	0	F6
Thermal Fault of medium temperatures 300-700 ^{0}C	0	2	1	F7
Thermal Fault of high temperatures > 700 C	0	2	2	F8

Even though IEC code method is suitable for the valuation of transformer insulation, no quantitative indication for the probability of each fault is given. In some cases, the DGA results cannot be coordinated by the prevailing codes making the diagnosis ineffective [Duval, 1989]. In many fault conditions, gases from different faults are mixed up resulting in perplexing ratios between different gas components. This can be overcome with the help of more sophisticated analysis methods such as the fuzzy diagnosis method as presented in our paper.

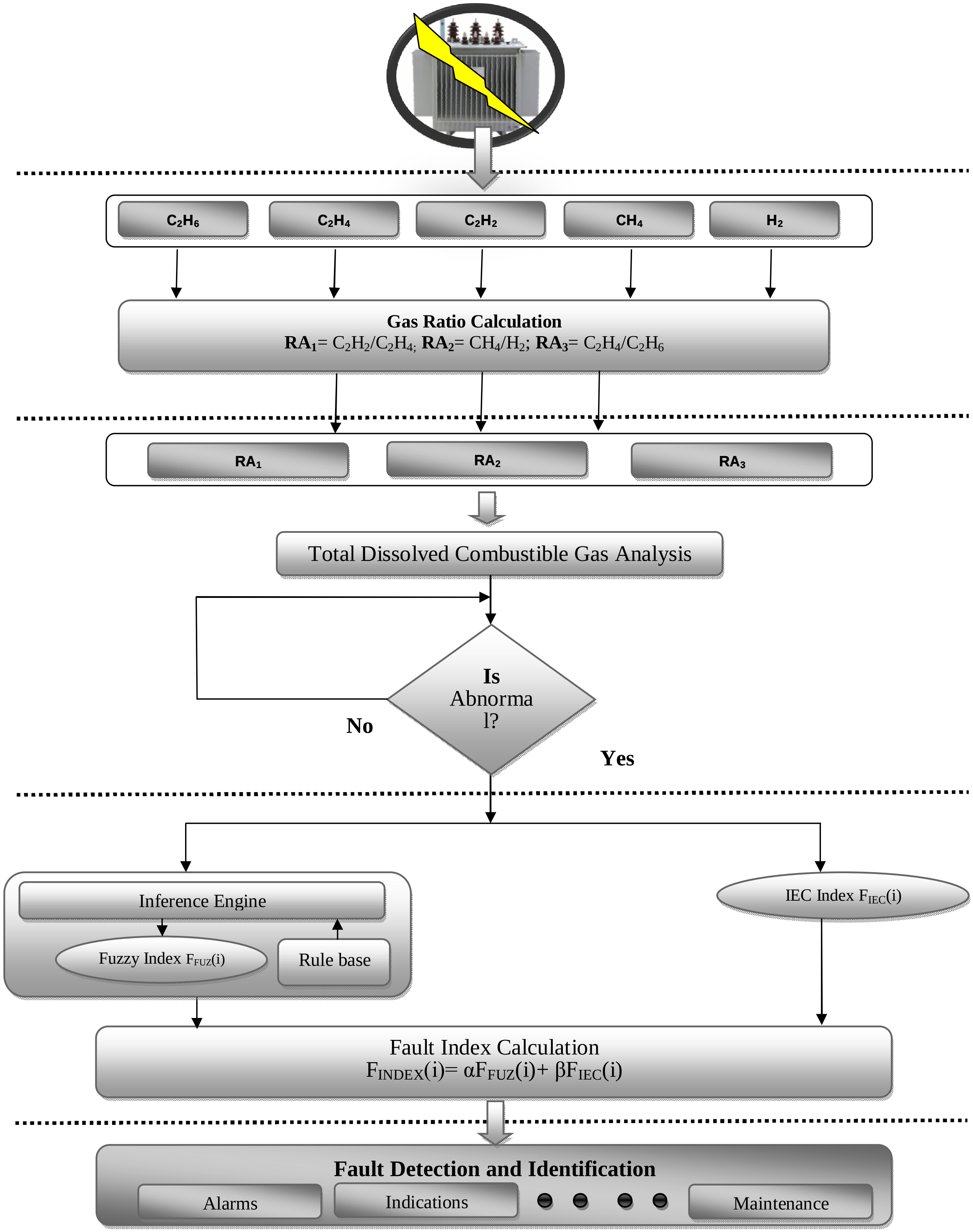

Fig. 1 Proposed Fuzzy IEC Expert System for Fault Diagnosis

IV. INTEGRATING FUZZY IEC EXPERT SYSTEM

The diagnosis is based on the prime dissolved gases and their proportions comparative to Total Dissolved Combustible Gas (TDCG). TDGA is the summation of the concentration of Hydrogen, Ethylene, Acetylene, Methane, Ethane, and Carbon Monoxide dissolved in oil. The absolute dissolved gas concentration (in PPM) and generation rates (PPM /DAY) are used to evaluate the rigorousness of any faults identified. For example according to [Huang,2003] and [Domerberg*et al.*, 1974]. If the absolute level of TDCG is above 720 PPM and consists around 63% of ethylene, then there is a signal of overheated oil. Close observing is advised if the TDCG generation rate go beyond 10 PPM/DAY. Table (3) shows the gases concentrations (PPM) for dissolved key gases method. Agreeing to the IEC codes in Table (1), for different ranges of ratios the three gas ratios (C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6) can be coded as 0, 1 and 2. Table (1) is reordered to give a clear relationship between the ranges of every single gas ratio and the equivalent IEC code, as shown in Table (4).

Table 4. The Modified IEC codes

Ratio – Code	Code 0	Code 1	Code 2
C_2H_2/C_2H_4	<0.1	0.1-3	3>
CH_4/H_2	0.1-1	<0.1	>1
C_2H_4/C_2H_6	<1	1-3	>3

Conferring to Table (2), Transformer faults can be recognized by the IEC codes of three gas ratios ($R_{A1}= C_2H_2/C_2H_4$, $R_{A2}= CH_4/H_2$, $R_{A3}= C_2H_4/C_2H_6$). For example, if the codes for a set of gas concentration are R_{A1}=0, R_{A2}=2 and R_{A3}=1, the transformer is detected to have a No.7 fault, (i.e. thermal fault of medium temperature 300 - 700'c.).In the IEC code diagnosis, actually the conventional logic AND and OR are used. For instance, the seventh fault is symbolized by:

F(7) = code $_{zero}$(R_{A1}) AND code $_{Two}$ (R_{A2}) AND code $_{One}$(R_{A3})

Where code$_{zero}$(R_{A1}), code $_{Two}$ (R_{A2}) and code $_{One}$(R_{A3})are the coded values of gas ratio R_{A1}, R_{A2} & R_{A3}respectively. They are either zero (false) or one (true) according to Table (3). Consequently, fault F(7) will be either one (true) or zero (false) by means of logic operation. Also (α and β) are random probability (0 to 1) and the best value are (0.73 and 0.27) respectively (trail and error method).In the fuzzy diagnosis method established, the IEC codes 0, 1 and 2 are reconstructed as fuzzy sets ZERO, ONE and TWO. Each gas ratio r can be characterized as a fuzzy vector [μ_{ZERO} (R_{A1}), μ_{ONE} (R_{A1}) , and μ_{TWO} (R_{A1})].

Where: μ_{ZERO} (R_{A1}), μ_{ONE} (R_{A1}), and μ_{TWO} (R_{A1}) are the membership functions of fuzzy code ZERO, ONE and TWO correspondingly. The input for Proposed Fuz-IEC method calculated from the chromatographic. Data are to diagnose the eight conditions. As 5 values of different gases are input to this method (Acetylene, Ethylene, Methane, Hydrogen, and Ethane) and the three features are ratios of gas concentrations

These three features, MH, AE, and EE are categorized as low (LOW), medium (MED), and high (HIGH) according to their membership in intervals in this fashion. Table 5 describes the Fuzzy-IEC Input Membership functions with ranges defined.

Table 5. Fuzzy Specifications

Ratios	Formula	Fuzzy Membership functions with Range
Ratio (RA1)	Methane / Hydrogen	**LOW** : Any value below 0.1. **MEDIUM :** Between 0.1 and 1 **HIGH** : > 1.0
Ratio (RA2)	Acetylene / Ethylene	**LOW** : Any value below 0.1. **MEDIUM :** Between 0.1 and 1 **HIGH** : > 1.0
Ratio (RA3)	Ethylene / Ethane	**LOW** : Any value below 0.1. **MEDIUM :** Between 0.1 and 1 **HIGH** : > 1.0

Table 3. Concentration (PPM) for dissolved key gases

Danger level	Hydrogen	Methane	Acetylene	Ethylene	Ethane	Carbon Monoxide	Carbon Dioxide
Normal	100	120	35	50	65	350	2500
Moderate	101 - 700	121 - 400	36 – 50	51 - 100	66 - 100	351 -570	2500-4000
High	701 - 1800	401 -1000	51 -80	101-200	101-150	571-1400	4001-10000
Severe	>1800	>1000	>80	>200	>150	>1400	>10000

***PPM** : Part Per Million

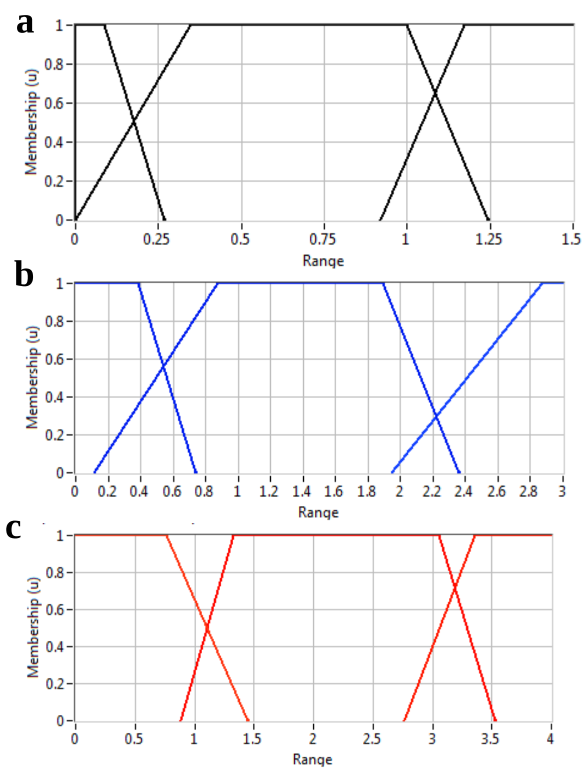

Figure 2 Input Membership Functions for (a) Ratio 1 (R_{A1}) ; (b) Ratio 2 (R_{A2}); (c) Ratio 3 (R_{A3})

Table 6. Knowledge Rule Base

		R_{A3}=LOW	R_{A3}=MED	R_{A3}=HIGH
R_{A1} - LOW	**R_{A2}=LOW**	F1	F1	F2
	R_{A2}=MED	----	F3	F3
	R_{A2}=HIGH	F4	----	----
R_{A1} - MED	**R_{A2}=LOW**	F0	F5	F5
	R_{A2}=MED	----	----	F3
	R_{A2}=HIGH	----	----	----
R_{A1}- HIGH	**R_{A2}=LOW**	----	F7	F8
	R_{A2}=MED	----	----	---
	R_{A2}=HIGH	----	----	----

For the enhanced IEC method, the input classifications R_{A1}=L, R_{A2}=H, and so on are given confidence factors considered as the degree of membership of the gas ratio in fuzzy versions of the intervals shown above.

Then the rules implicit in Table 6 are applied to develop confidence factors for all the IEC diagnoses [IEEE Std. C57, 1992]. The fuzzy membership functions for IEC input classifications are graphed in Figure (2a) for R_{A1}, figure (2b) for R_{A2}., and figure (2b) for R_{A3}.To ensure consistency with the standard IEC method, the membership functions of the fuzzy intervals are well-defined so that they equal 0.5 at the endpoints of the corresponding "crisp" intervals. This guarantees that the cf of a diagnosis is greater than 0.5 if and only if the standard Rogers method creates that diagnosis. Since the cf is only a rough "strength of assertion" indicator and not a probability, the exact shape and width of the membership function graphs is not critical [IEEE Std. C57, 1992].

V. Results and Discussions

As the information available about the history of the transformer and test data is really high, the possibility for correct diagnosis of the health of the unit is really high [1]. A baseline transformer test information should be established when the transformer is new or when possible afterwards. Launching such a reference point for gas concentrations in new or repaired transformers and tailed up by a routine monitoring program is an important element in the application of the traditional DGA methods. Monitoring the health of a transformer must be done on a routine basis and can start anytime, not just for new unit. The proposed method is applied to famous data of transformers published in literature [8, 9, and 10] and those from the field.

Example (i) : The transformer began operation in 1971 and the unit had affected by an arc tracing fault in August 1989. After repairing and degassing a special gas fingerprint of the transformer was designed. Table 7 provides the DGA samples and the relationship of the fault analysis by the proposed proof belief method with IEC/IEEE method. The IEC/IEEE method specified arcing fault for sample 1-3 while the fault type of sample 1 could not be identified. The proposed method diagnosis a thermal fault and discharge in sample 2 and 3 correspondingly.

Table 7. Example (i) DGA data and Comparative Analysis

Sample no.	Date of sample	H_2	CH_4	C2H4	C2H6	C2H2	IEC/IEEE method	Proposed method	Comparison
1	8/19/1989	85	126	224	46	96	ND	Thermal and discharge	–
2	9/27/1989	142	118	193	31	92	F_4	Discharge thermal	Match
3	1/15/1990	300	45	101	17	225	F_4	Discharge	Match
4	2/23/1990	206	42	82	16	221	F_4	Discharge	Match
5	4/10/1990	3091	46	101	17	239	ND	Discharge	–

The sample 2 values of various gases against time (in days) at fault condition in Fig. 3. The proposed method specifies that when the transformer was put away in service after repair there was re-development of an arc inside the Unit.

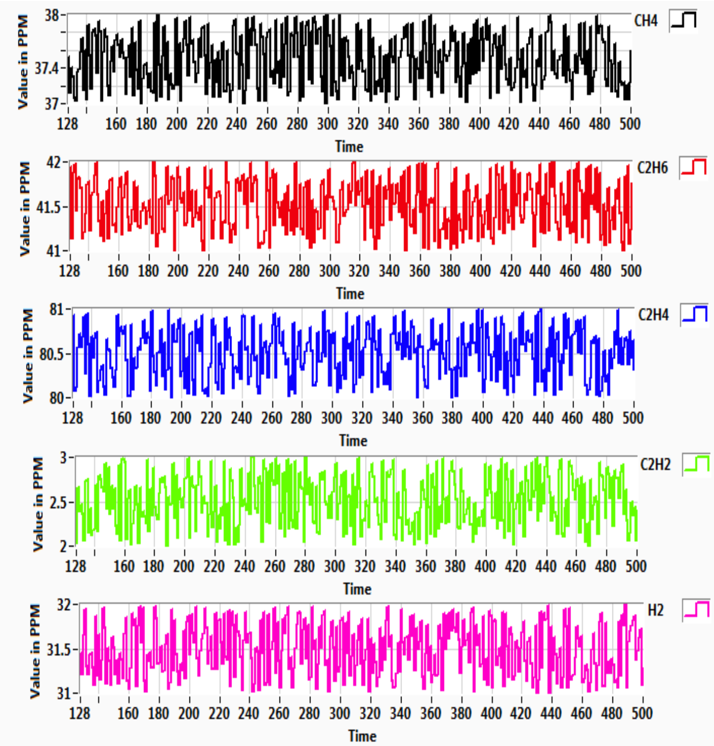

Fig.3 Example (i): Logged data for Sample 2

Example (ii): The 50 MV A, 11/110 kV, Generator Transformer had been in service for six years. The DGA results revealed an initial increasing trend and later become stabilized values making a definite prediction problematic.

So, closer monitoring of the transformer was suggested. Table 8 gives the DGA data and the fault analysis by IEC/IEEE method and the proposed method. The DGA results specified that between February, 2000 and March, 2001 a thermal fault established. The concentration of C_2H_4 was found to be increasing indicating a thermal fault emerging which is confirmed by the IEC/IEEE method.

By the proposed method occurrence of thermal fault is indicated in the samples and there is an increasing tendency of thermal fault level from the logged data and seen in Fig. 4, the initial accumulative trend of the thermal fault and also the accumulative weighed value propose that the transformer should be pulled out of service and internal assessment be carried out before the developing initial fault causes catastrophic blockbusting and breakdown of the Unit. It is observed that the proposed method can be used to observe the trend of fault development in a transformer over the period of time.

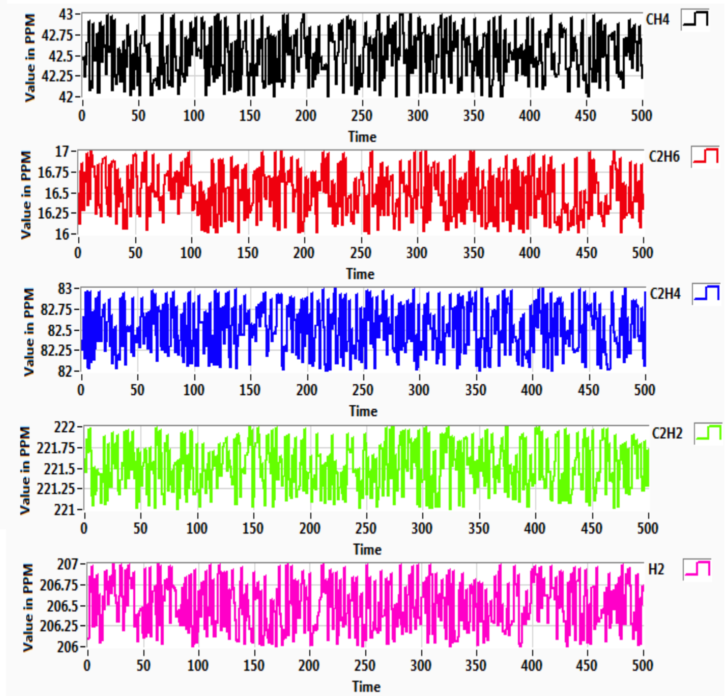

Fig.4 Example (ii): Logged data for Sample 4

The above figure depicts the data logged when the transformer is at fault condition, then it is being used for fault detection and identification by Fuzzy IEC Expert system. So as to study the performance of the proposed method the results of the both examples calculated are compared in Figure 5.

Table 7. Example (i) DGA data and Comparative Analysis

Sample no.	Date	H_2	CH_4	C2H4	C2H6	C2H2	IEC/IEEE method	Proposed method	Comparison
1	Feb-00	16	79	45	46	0	F_0	Not applicable and partial discharge	–
2	Mar-01	31	39	82	43	3	F_7	Thermal	Match
3	May-01	14	44	75	36	0	F_7	Thermal	Match
4	May-02	11	55	212	53	3	F_8	Thermal and partial discharge	Match

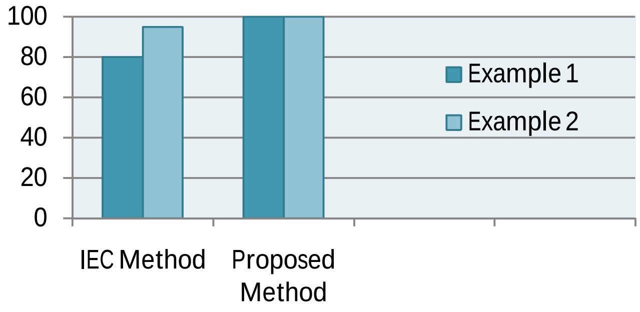

Fig.5 Proportional Analysis of IEC and Proposed Method

VI. CONCLUSION

The strength of the proposed method lies in the fact that the percentage concentration of the gases and the gas ratios are used as the input to Fuzzy IEC expert system, thus all the drawback of conventional methods are removed and the advantaged of AI techniques included. The integration of fuzzy logic and IEC method outputs has given reliable results and removes any conflict in their diagnosis. When the proposed method was applied to a transformer unit the results that were obtained for the available samples were consistent with the actual fault. The improvements in the conventional IEC code method are due to the more truthful representation of the relationship between the fault type and the dissolved gas levels with fuzzy member ship function as shown in the results, where on top of determining the fault in transformer.

Testing on actual DGA data of transformers shows the good diagnosis ability of the proposed method. The results are consistent with the actual faults and also fault type could be identified when the traditional methods are unable to do so. Using the proposed method the decision regarding maintenance need not be dependent only on the operator/expert opinion but can be scientifically deduced using the proposed diagnostic method. Based on the degree of belief the transformer units can be ranked in order for decision making for routine maintenance/removal from service for preventive maintenance strategies. It is expected that the operators would believe more in the degree of belief rather than taking a statement of a particular type of fault given by the different methods which at times are contradicting.

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