Power Transformer Fault Detection and Isolation based on Intuitionistic Fuzzy System

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Abstract — Power transformer oil using Dissolved Gas Analysis (DGA) is the most used diagnosis method for power transformer faults. Though various methods have been developed to interpret DGA results, sometimes they fail to determine the faults. Forecasting of the ratios of key-gas in transformer oil is a complicated problem due to its non-linearity and the small amount of training data. This paper presents Intuitionistic Fuzzy System (IFS) to diagnose several faults in a transformer. This proposed 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. This 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, IFS, fault diagnosis.

1. 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 [2,8], Duvals Triangle, CIGRE Regulations, 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 [17]. This paper is planned as follows: Introduction followed by dissolved gas analysis (DGA) explanation, IEC Code ratio scheme explained with its tables, Integrating Intuitionistic Fuzzy IEC scheme structures (IFS-IEC) has been demonstrated, results and Diagnosis Example are taken and the conclusion is made.

2. PRELIMINARIES

2.1 IEC Gas Ratio Method

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.

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

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.

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_2 H_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

2.2 Intuitionistic Fuzzy Systems

In 1983 K. Atanassov [2] proposed a generalization of the notion of fuzzy set, known as Intuitionistic fuzzy set (IFS). He introduced a new component degree of non-membership in the definition of these sets and studied the properties of a new object so defined. Since then, a great number of theoretical and practical result approach in the area of IFSs. In addition to the degree of membership known from fuzzy sets, here a new degree is introduced called degree of non-membership with requirement that their sum be less than or equal to 1. The complement of the two degree to 1 is regarded as a degree of uncertainty. The IFS where defined as an extension of the ordinary fuzzy sets. As opposed to a fuzzy set in X given by

$$B = \{(x, \mu_B(x)) | x \in X\}$$

Where, $\mu_B(x) : X \rightarrow [0, 1]$ is the membership function of the fuzzy set B, an Intuitionistic fuzzy set A is given by

$$A = \{(x, \mu_A(x)), v_A(x) | x \in X\}$$

Where, $\mu_A(x) : X \rightarrow [0, 1]$ and $v_A : X \rightarrow [0, 1]$ are such that

$$0 \leq \mu_A + \mu_B \geq 1$$

And $\mu_A(x);\ v_A(x) \in [0\ 1]$ denote a degree of membership and a degree of non-membership of$x \in A$, respectively. For each Intuitionistic fuzzy set in X, we will call

$$\pi_A(x) = 1 - \mu_A(x) - v_A(x)$$

A hesitation margin (or Intuitionistic fuzzy index) of $x \in A$ and, it expresses a hesitation degree of whether x belongs to A or not. It is obvious that $0 \leq \pi_A(x) \geq 1$, for each $x \in A$.

Since the Intuitionistic fuzzy sets being a generalization of fuzzy sets give us an additional possibility to represent imperfect knowledge, they can make it possible many real problems in a more adequate way.

3. Proposed IFS Based Transformer Fault Diagnosis

An intuitionistic Fuzzy system has to consider the fact that we have the membership μ functions as well as the non-membership υ functions. In this paper, we propose that the conclusion of an intuitionistic fuzzy system can be a linear combination of the results of two traditional fuzzy systems, one for the membership functions and the other for the non-membership functions. With the following equation we can calculate the total output as a linear combination of IFS. $IFS = (1 - \pi)F_{Z_\mu} + F_{Z_v}$ Where F_{Z_μ} is the traditional output of a fuzzy system using the membership function μ, and F_{Z_v} is the output of a fuzzy system using the non-membership function υ, and π is hesitation margin or intuitionistic index. The advantage of this technique for computing the output of IFS is that we can use our previous machinery of traditional fuzzy systems for computing and then, we only perform a weighted average of both results to obtain the final output of IFS[17].

3.1 IFS-IEC Fault Diagnosis

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 (3).

Table 3 IEC Ratio 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 [$\mu_{ZERO}(R_{A1})$, $\mu_{ONE}(R_{A1})$, and $\mu_{TWO}(R_{A1})$]. Where: $\mu_{ZERO}(R_{A1})$, $\mu_{ONE}(R_{A1})$, and $\mu_{TWO}(R_{A1})$ 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 4 describes the Fuzzy-IEC Input Membership functions with ranges defined.

Table 4 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

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.

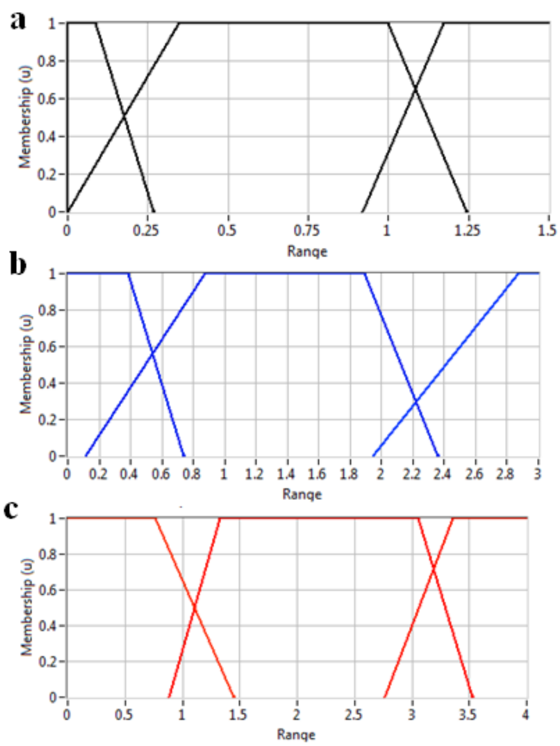

Figure 2 Input Membership Functions for (a) Ratio 1 (R_{A1}) ; (b) Ratio 2 (R_{A2}); (c) Ratio 3 (R_{A3})

Table 5 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	----	----	----

Then the rules implicit in Table 5 are applied to develop confidence factors for all the IEC diagnoses [IEEE Std. C57, 1992]. We will consider for simplicity uniform triangular membership function for the linguistic value low, medium and high of the input linguistic variable of IEC ratio method uses three ratios R_{A1}, R_{A2}, and R_{A3}. 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}. "Figure 2," shows the non-membership functions for R2 ratio the linguistic values of the input variable. It is clear from "Figure 1," and "Figure 2," that in this case the membership and non-membership functions for R2 ratio are not complementary, which is due to the fact that we have an intuitionistic fuzzy system. From Figure 1 and Figure 2 we can clearly see that the hesitation margin p: is 0.05 for both cases. Of course, we can compare this intuitionistic fuzzy. After the fuzzy number of R_{A1}, R_{A2}, and R_{A3} had been obtained, reference to the fault coding interpretation table was required. Similarly the fuzzify non-member function ratios to the interpretation table can be accomplish by averaging the all the fault conditions in Table I. An intuitionistic fuzzy system has to consider the fact that we have the membership function μ each ratio R1, R2 and R5 had been obtained. As well as the non-membership Function υ each ratio R1, R2 and R5 had been obtained. The intuitionistic fuzzy system can be a linear combination of the result of two traditional fuzzy system one for the membership function μ for each ratio R1, R2 and R5 and other for the non-membership function υ for each ratio R1, R2 and R5. This IFS use IEEE three key gas diagnosis table for fault diagnosis of transformer. As for traditional system, Boolean operations of "or" and "and" were used to obtain the combinations of the codes. If then- else rules will then be used to determine fault condition, after a code combination had been formed. In the IFS Roger's key ratio method, the Boolean operation of "or" and "and" can be simulated with the mathematical operation of "+" and "□".The if then-else rules will still be used to determine the individual fault condition of the transformer.

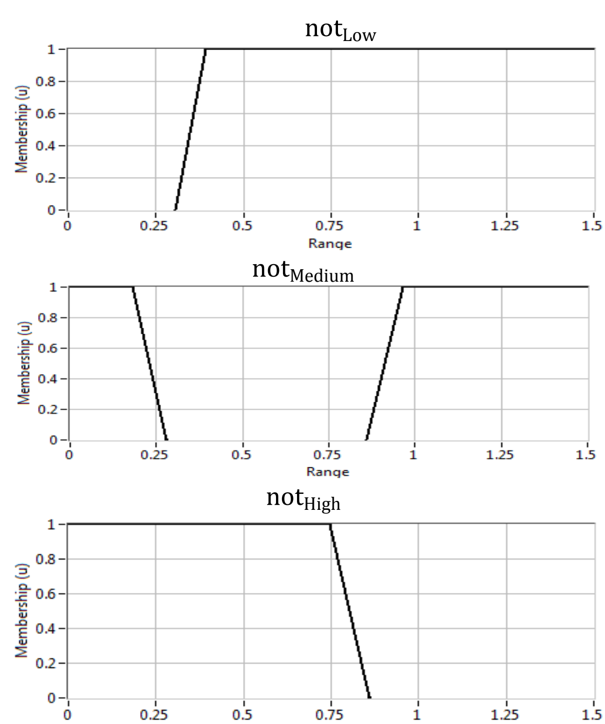

Figure 2 Input Membership Functions for (a) Ratio 1 (R_{A1}) ; (b) Ratio 2 (R_{A2}); (c) Ratio 3 (R_{A3})

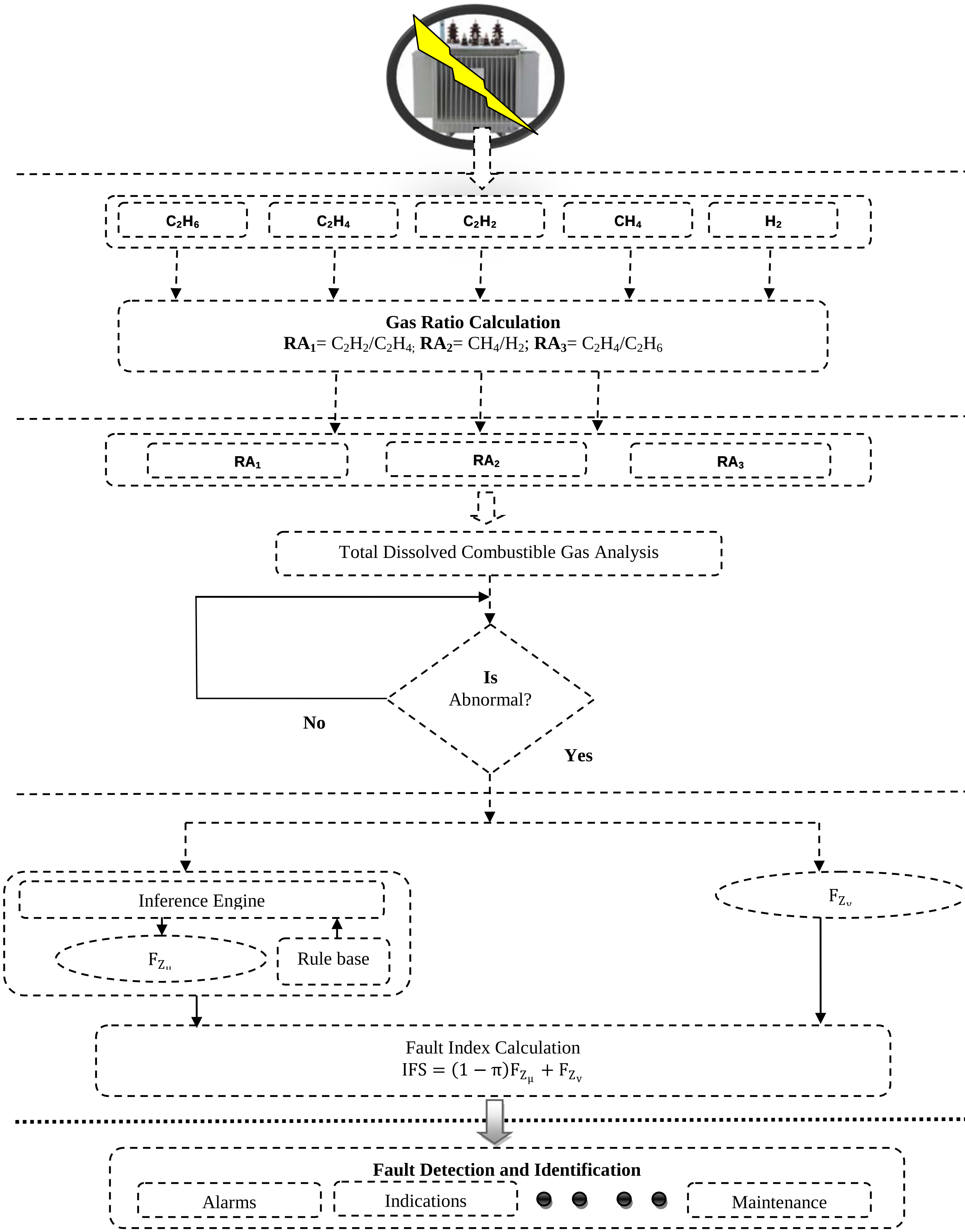

Fig. 1 Proposed Intuitionistic Fuzzy Expert System for Fault

4. 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 17] 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.

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.

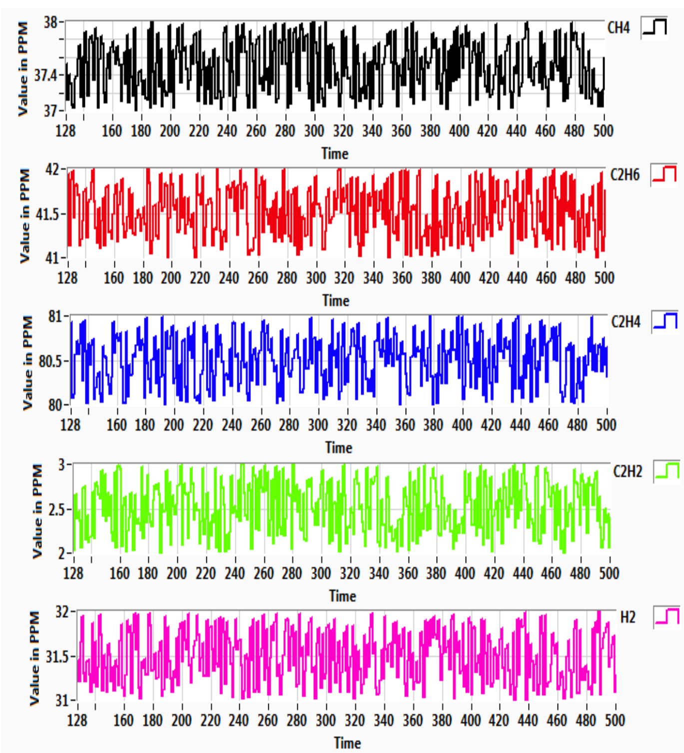

Fig.3 Example (i): Logged data for Sample 2

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.

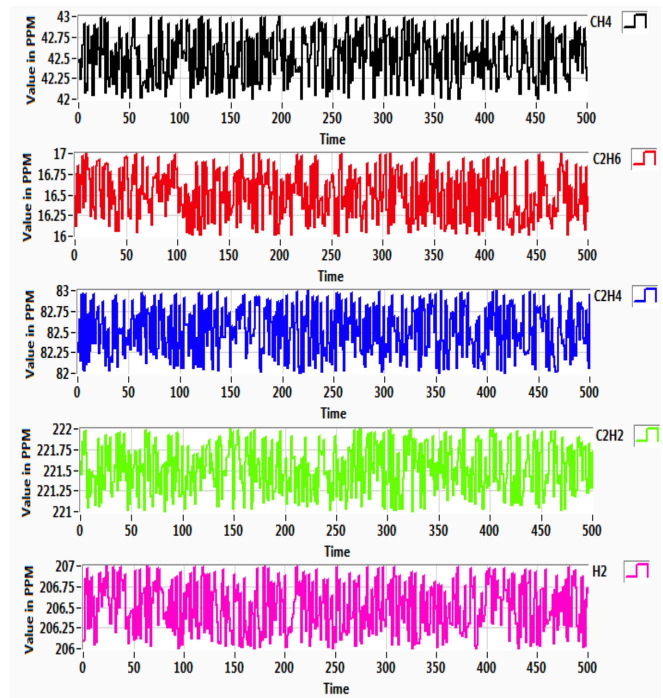

Fig.4 Example (ii): Logged data for Sample 3

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.	H_2	CH_4	C2H4	C2H6	C2H2	IEC/IEEE method	Proposed method	Comparison
1	90	120	220	48	97	ND	Thermal and discharge	–
2	145	118	195	30	95	F_4	Discharge thermal	Match
3	300	45	101	17	225	F_4	Discharge	Match

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

Sample no.	H_2	CH_4	C2H4	C2H6	C2H2	IEC/IEEE method	Proposed method	Comparison
1	31	39	82	43	3	F_7	Thermal	Match
2	14	44	75	36	0	F_7	Thermal	Match
3	11	55	212	53	3	F_8	Thermal and partial discharge	Match

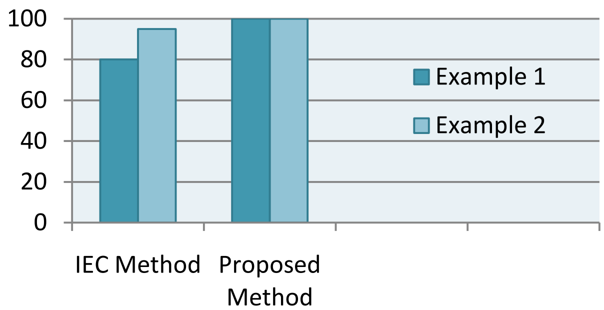

Fig.5 Proportional Analysis of IEC and Proposed Method

5. CONCLUSION

The non-destructive technique for fault evacuation of transformer can be done by monitoring gas in transformer. There are number of technique available to predict fault in transformer by analysis of DGA data, but no one technique are use to predict fault in transformer properly. The experimental results are studied by following techniques traditional IEC method, and IFS IEC key gas method. 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 when the traditional methods are unable to do so. The improvements in the proposed 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. 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.

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