Diagnosis of Power Transformer Faults based on Five Fuzzy Ratio Method

N.K.DHOTE
Associate Professor, Electrical Engineering Department
St. Vincent Pallotti College of Engineering & Technology, Wardha Road,Nagpur,
INDIA
nitindhote@yahoo.com

Dr. J.B.HELONDE
Principal, ITM College of Engineering, Kamptee Road,Nagpur.
INDIA
jb_helonde@rediffmail.com

Abstract: Dissolved Gas Analysis is one of the most useful method to detect incipient faults in transformer. Amongst the conventional DGA methods, IEC three ratio method is widely used. One of the disadvantages in its present form is that a significant number of DGA results in- service fall outside the existing IEC codes and cannot be diagnosed. To overcome this limitation, additional eighteen new combinations to the existing nine are proposed in this paper. Further, Ratio codes are quantized to define the crisp boundaries of 0,1 and 2. In practice these boundaries are non crisp (Fuzzy) especially under multiple faults condition. These codes could lead to errors in diagnosis moving across the crisp boundaries from one fault to another. To overcome these limitations, Five Fuzzy ratio method for diagnosis of multiple faults is developed. The paper used 100 different cases to test the accuracy of these methods in interpreting the transformer condition.

Key-words: Expert System (ES),Dissolved Gas Analysis(DGA),International Electro Commission Method (IEC), Incipient Faults, Power Transformer, Fault Diagnosis, Fuzzy Diagnostic System, Ratio Methods.

1. Introduction

Power transformer is major component of power system which has no substitute for its major role. A transformer may function well externally with monitors, while some incipient deterioration may occur internally to cause fatal problem in later development. Nearly 80 % of faults result from incipient deteriorations. Therefore, faults should be identified and avoided at earliest possible stage by some predictive maintenance technique. Like any diagnosis problems, diagnosis of an oil-immersed transformer is a skilled task. Dissolved Gas Analysis (DGA) is reliable technique for detection of incipient faults in oil filled power transformer. Like a blood test or a scanner examination of the human body, it can warn about an impending problem, give an early diagnosis and increase the chances of finding the appropriate cure. The operating principle [1]-[3] is based on slight harmless deterioration of the insulation that accompanies incipient faults, in the form of arcs or sparks resulting from dielectric breakdown of weak or overstressed parts of the insulation, or hot spot due to abnormally high current densities in conductors. Whatever the cause, these stresses will result in chemical breakdown of some of the oil or cellulose molecules of the dielectric insulation. The main degradation products are gases, which entirely or partially dissolve in the oil where they are easily detected at the ppm (per part million) level by Gas Chromatography [4]-[9]. It is a technique of separation, identification and quantification of mixtures of gases. By using gas chromatography [4]-[9] to analyze the gases dissolved in transformer's insulating oil, it becomes feasible to judge the incipient fault types. The main gases formed as a result of electrical and thermal faults in transformers and evaluated by chromatography are H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2. Their relative proportions have been correlated through empirical observations and laboratory simulations, with various types of transformer encountered in service. Even under normal transformer operational conditions, some of these gases may be formed inside. Thus, it is necessary to build concentration norms from a sufficiently large sampling to assess the statistics.

2. DGA interpretation

If an incipient fault is present, the individual gas concentration, Total Combustible Gas (TCG) [10] and generating rate [10]-[12] are all significantly increased. Many DGA interpretative methods such as Key gas method [13]-[14], Dornerburg [13]-[15], Rogers [16] have been reported. Each of these techniques has its own advantages and limitations. These techniques do not necessarily reach to the same conclusion. The accuracy depends upon the expertise of the person handling the analysis. DGA is not science, but an art. The most widely used ratio method for this purpose is the IEC Standard 60599 [11] which is depicted in Table 1. One of the disadvantages in its present form is that a significant number of DGA results in- service fall outside the existing IEC codes and cannot be diagnosed. To overcome this limitation, additional eighteen new combinations to the existing nine are proposed in this paper, which are displayed in Table 2.

3. Proposed diagnostic expert system

Expert system is one of the areas of Artificial Intelligence (AI) which has moved out from research laboratory to the real word and has shown its potential in industrial and commercial applications .An expert system is a computer system which can act as human expert within one particular field of knowledge .The expert system embodies knowledge about one specific problem domain and possesses the ability to apply this knowledge to solve problem domain. Ideally the expert system can also learn from its mistakes and gain experience from its successes and failures. The system should be able to explain the reasoning behind the way in which it has aimed at a particular conclusion.

3.1 Selection of development tool

For the development of any expert system, there should be proper selection of a development tool. The different packages i.e., VP-Expert, Shell, Rule master, etc. can also be used for development, but these packages have their own limitations, since they use their own rules and instructions. But a computer language is more flexible and the user can develop his methodology for the program formulation. So instead of using package, we can use computer language for expert system development. The language chosen should be simple and declarative. 'MATLAB' has these facilities. With the help of this interface, the capability of tracing, explaining and training in an expert system is greatly signified.

3.2 Experienced diagnostic procedure

As shown in figure 1, the overall procedure of routine maintenance for transformer is listed. The core of this procedure is based on the implementation of DGA techniques. The gas ratio Method is a significant knowledge source. The Key gas method [13]-[14], Dornenburg [13]-[15], Rogers [16] and IEC [10]-[12] approaches have been implemented together. The single ratio method is unable to cover all possible cases, other diagnostic expertise should be used to assist this method. Synthetic expertise method and database records have been incorporated to complete these limitations.
The first step of this diagnostic procedure begins by asking DGA for a sample to be tested, more important information about transformer's condition such as VA rating, Voltage rating, volume of oil and date of installation of transformer must be known for further inference. If the transformer is not degassed after previous diagnosis, then rate of evolution of total combustible gases TCG [10]-[12] is found. If rate of evolution is normal (less than 2.8 litre/day), further diagnosis can be bypassed. For abnormal rate of TCG [10-12], Permissible limits for different gases are checked. If gas concentrations exceed permissible limits, different DGA interpretative methods [10-16] are used to diagnose transformer fault type. If all methods give different results, proposed system diagnosis is adopted. If gas ratios lie in the boundary of the ratio codes, fuzzy diagnostic expert system is used. Probable multiple faults are diagnosed. After these procedures, different severity degrees are assigned to allow appropriate maintenance suggestions.

4. Fuzzy diagnostic expert system

There are lots of indeterminate factors in process of transformer fault diagnosis whose influence to the transformer operation status is usually fuzzy and uncertain. Ratio codes are quantized to define the crisp boundaries of 0,1 and 2. In practice these boundaries are non crisp (Fuzzy) especially under multiple faults condition. These codes could lead to errors in diagnosis moving across the crisp boundaries from one fault to another. To overcome these limitations, Fuzzy System for diagnosis of multiple faults is developed.

Table 1
IEC/IEEE codes for the interpretation of DGA results

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Range of gas ratio
0	1	0	< 0.1
1	0	0	0.1-1
1	2	1	1-3
2	2	2	Greater than 3
C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Characteristic Fault
0	0	0	Normal ageing.
0	0	1	Thermal fault of low temp <150 Deg. C.
0	1	0	Partial discharge of low energy density.
0	2	0	Thermal fault of low temp between 150-300 Deg. C.
0	2	1	Thermal fault of medium temp between 300-700 Deg. C.
0	2	2	Thermal fault of high temp >700 Deg. C.
1	0	1	Discharges of low energy, Continuous sparking.
1	0	2	Discharge of high energy, Arcing.
1	1	0	Partial discharge of high energy density, Corona.

Table 2
Additional codes for the interpretations of DGA results

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Characteristic Fault
0	0	2	Partial discharge of low energy
0	1	1	Thermal fault of low temp between 150-300 Deg. C
0	1	2	Thermal fault of low temp <150 Deg. C.
1	0	0	Flashover, Intermittent sparking
1	1	1	Thermal fault of low temp between 150-300 Deg. C.
1	1	2	Thermal fault of high temp >700 Deg. C.
1	2	0	Core and tank circulating currents.
1	2	1	Winding Circulating currents.
1	2	2	Core and tank circulating currents.
2	0	0	Partial discharge of high energy density, Corona
2	0	1	Discharge of high energy, Arcing.
2	0	2	Discharges of low energy, Continuous sparking
2	1	0	Partial discharge of high energy density, Corona
2	1	1	Discharge of high energy, Arcing.
2	1	2	Discharges of low energy, Continuous sparking
2	2	0	Severe arcing, Overheating of oil.(> 1000 Deg. C)
2	2	1	
2	2	2	

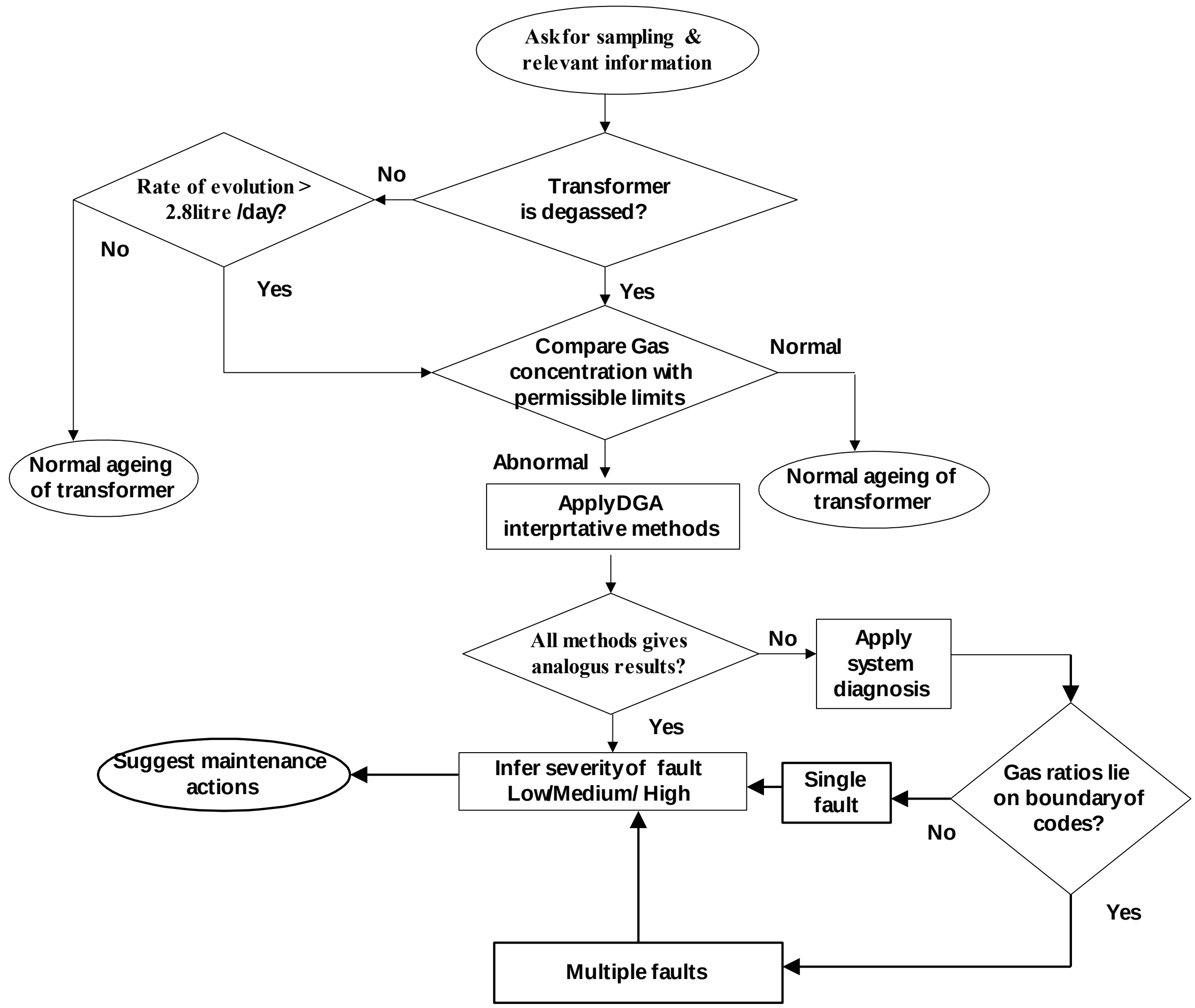

Fig.1 Flow chart of proposed system diagnosis

4.1 Fuzzy set description

An ordinary set can be characterized as a binary function. Elements in the set can be assigned to1 and remaining elements of the universe can be assigned to 0. The function is generalised so that value assigned to the elements of the universal set located within a specified range which indicates membership grades of these elements within the sets, such function is called membership function [17-20] and the corresponding set is a fuzzy set.

4.2 Fuzzy inference system (FIS)

Sugeno method [21-24] is most commonly used fuzzy inference method.

A typical rule in Sugeno fuzzy model has the form, if input1 =x and input2=y, then output z=ax+by.

The output level z of each rule is weighted by firing strength w of the rule.

For example ,if input1 =f(x) and input2=f(y) ,then firing strength $w_{i\ =\ AND}$ method (F1(x),F2(y)),

Where F1(x) and F2(y) are the membership functions for input1 and input2.The final output of the system is weighted average of all the rule output which is given as,

$$\text{Final Output} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \quad (1)$$

Where N is number of rules. Sugeno rule operates as per diagram shown in Fig.2

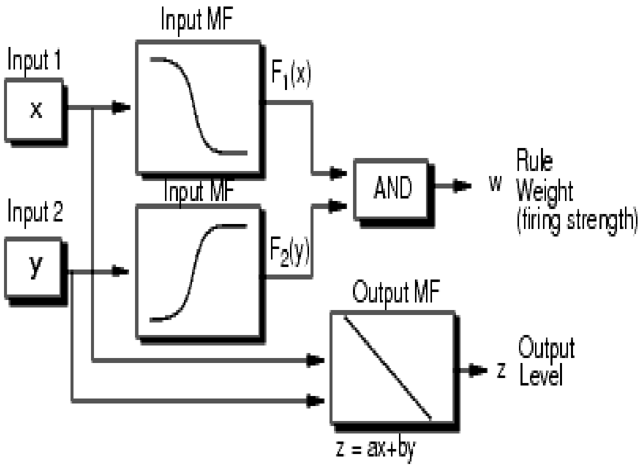

Fig.2 Sugeno Model

4.3 Proposed fuzzy control algorithm

The proposed FIS editor prepared using MATLAB Fuzzy Logic Toolbox is shown in Fig.3.

This fuzzy system consists of 3 ratios C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 as inputs. Each ratio is fuzzified as Very Low, Low, Medium, High and Very High according to membership intervals as defined in Table 3;

The membership boundaries of Low and High fuzzy are fuzzified by using triangular function.

$$T(u; a, b, c) = \begin{cases} 0 & \text{for } u<a \\ (u-a)/(b-a) & \text{for } a <= u <= b \\ (c-u)/(c-b) & \text{for } b <= u <= c \\ 0 & \text{for } u>c \end{cases}$$

The membership boundaries of other fuzzy ratios are fuzzified by using trapezoidal function.

$$T(u; a, b, c) = \begin{cases} 0 & \text{for } u<a \\ (u-a)/(b-a) & \text{for } a <= u <= b \\ 1 & \text{for } b <= u <= c \\ (d-u)/(d-b) & \text{for } b <= u <= c \\ 0 & \text{for } u>c \end{cases}$$

Membership function for C_2H_4/C_2H_6 ratio is given in Fig.4.The fuzzy system comprises of two outputs showing probable mixed faults. Each output has 13 Fault type as membership functions which is shown in Table 4. Severity is assigned to each fault type on the basis of experienced field data .

System comprises of 125 rules. 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. Some example of the fuzzy rules are shown in rule editor (Fig.5) .

For the development of suitable fuzzy control algorithm , Simulink model is developed in MATLAB which is given below (Fig.6).

Although the ratio codes rules appears strictly defined, borderline cases with gas ratios on or near the line between code 0, 1 or 2 allows fuzzy inference system to interpret membership function of these rules flexibly and classify these cases under two different fault types. In accordance with expert experience and field knowledge, severity can be assigned to each fault type. For the fuzzy logic control, Sugeno [21] model is used. FIS derives output fuzzy sets from judging all the fuzzy rules by finding the weighted average of all 125 fuzzy rules output.

5. Implementation of proposed expert system

An expert system is developed based on the proposed interpretative rules and diagnostic procedure of an overall system. To demonstrate the feasibility of this expert system in diagnosis, 100 DGA gas records supplied by power companies CPRI, BHEL and NTPC (India) have been tested.

Accuracy is calculated in two different ways,

a) When considering only number of predictions, percentage accuracy is given as

$$A_p = (T_R / Tp) *100 \qquad (2)$$

where T_R is number of correct predictions and TP is total number of the predictions,

b) When considering total number of cases, percentage accuracy is given as

$$AR = (T_R/T_C)*100 \qquad (3)$$

Where Tc is total number of cases

Accuracy values for different methods are compared and summarised in Table 5.

Table 3
Fuzzy ratios for membership interval

Fuzzy Ratio	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Very Low	U<0.09	U<0.09	U<0.9
Low	0.09<=U<=0.11	0.09<=U<=0.11	0.9<=U<=1.1
Medium	0.11<=U<=2.9	0.11<=U<=0.9	1.1<=U<=2.9
High	2.9<=U<=3.1	0.9<=U<=1.1	2.9<=U<=3.1
Very High	U>3.1	U>1.1	U>3.1

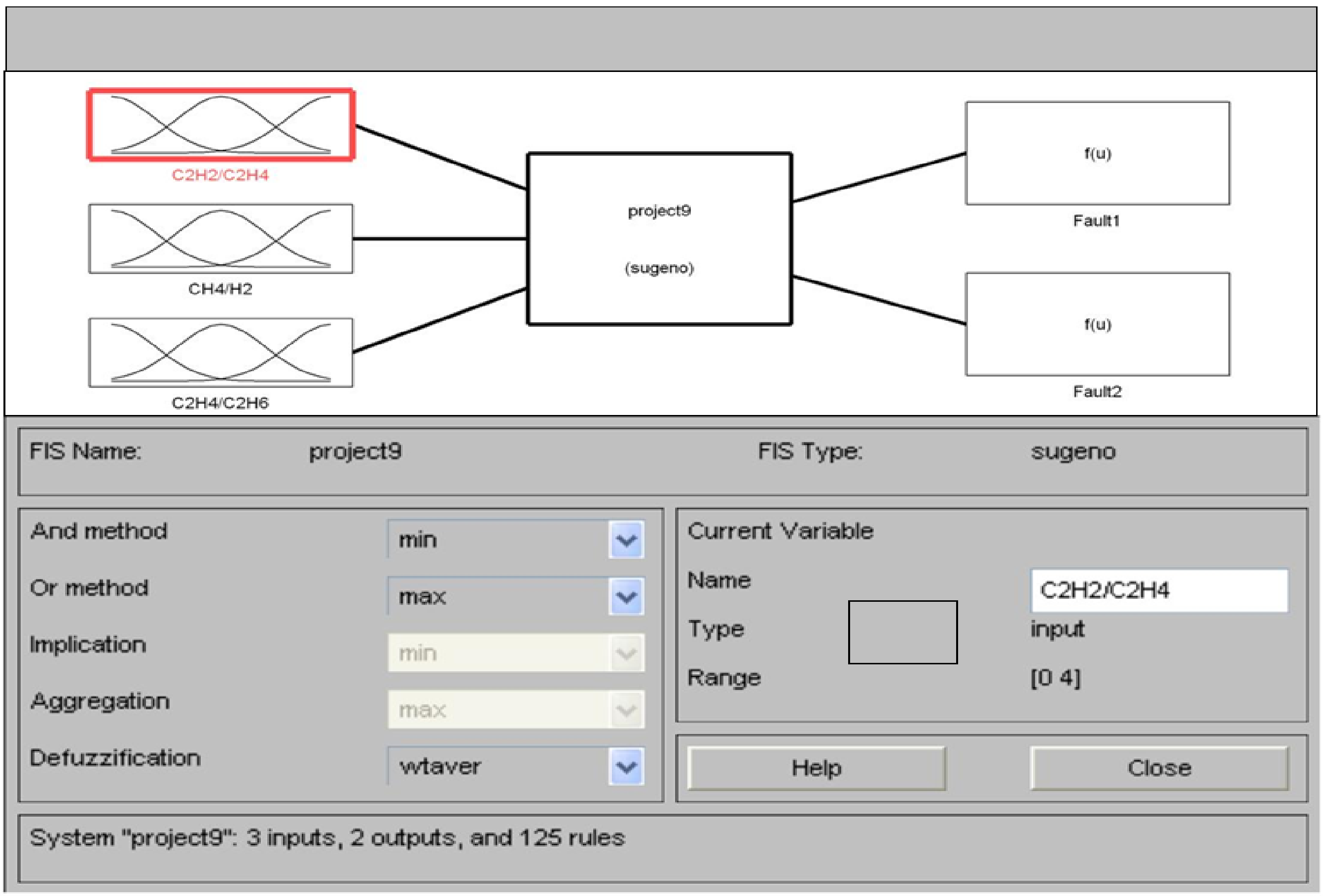

Fig.3 FIS Editor

Table 4
Fault code and type

Fault code	Fault Type
F0	Normal
F1	Thermal Fault -Very Low (<150Deg.C.)
F2	Partial Discharge –Low
F3	Thermal Fault-Low (Temp. Between 150-300Deg.c)
F4	Intermittent Sparking
F5	Continuous Sparking
F6	Thermal Fault-Medium (Temp. Between 300-700Deg.C)
F7	Winding circulating currents
F8	Core circulating currents
F9	Partial discharge of high energy, Corona
F10	Thermal fault –High (Temp. > 700Deg.C)
F11	Arcing
F12	Severe arcing, overheating of oil (Temp.>1000Deg.C)

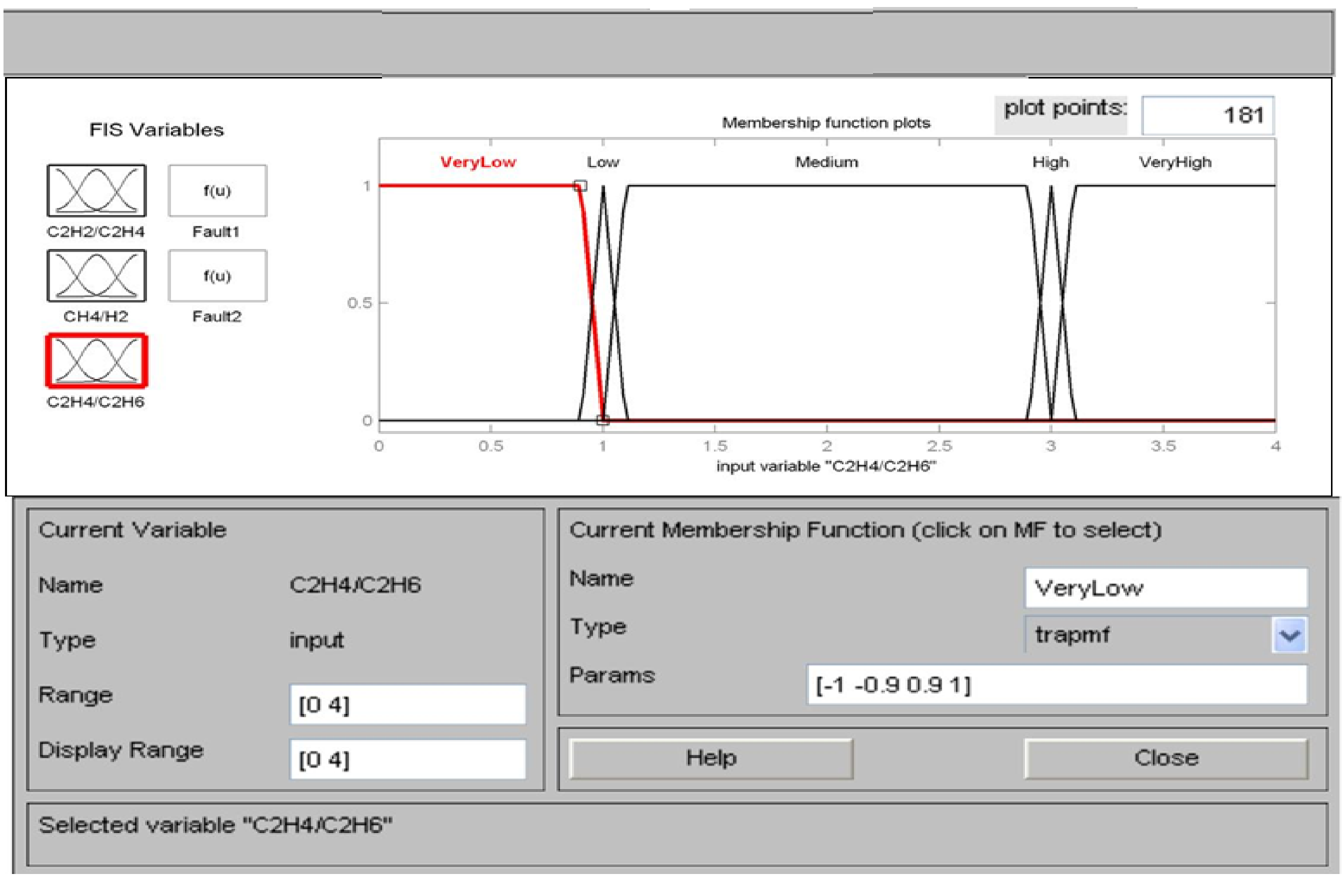

Fig.4 Membership function for C2H4/C2H6 ratio

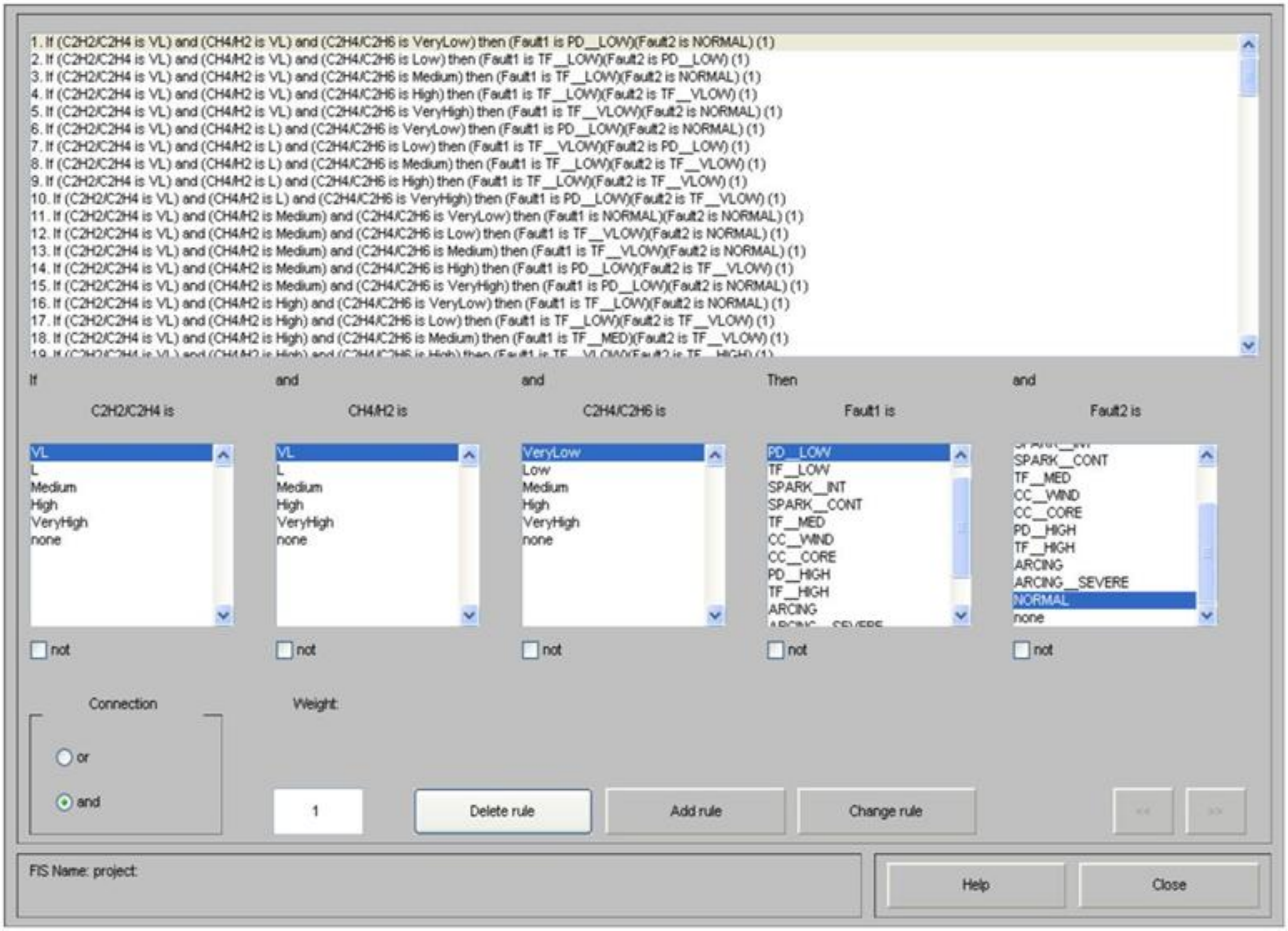

Fig.5 Rule Editor

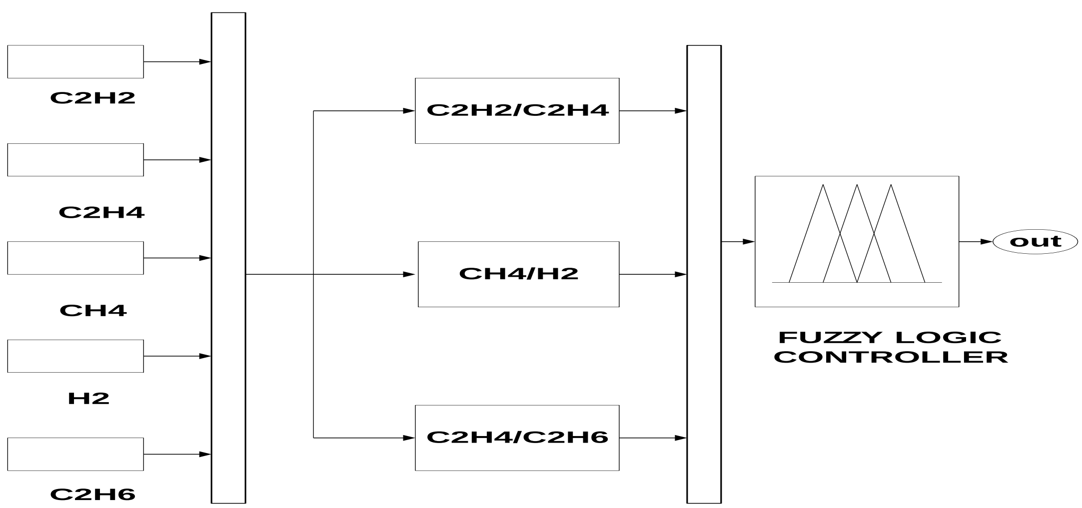

Fig.6 Simulink model for fuzzy system.

Table 5
Comparison of accuracy of different methods

	Key Gas	Dornenburg	Roger	IEC method	Proposed diagnosis without fuzzy	Proposed diagnosis with fuzzy
Total cases	100	100	100	100	100	100
Total number of predictions	100	38	45	56	100	100
Number of correct predictions	53	24	30	53	78	91
% Accuracy A_p	53	63.16	66.67	94.64	78	91
% Accuracy A_T	53	24	30	56	78	91

6. Case study

NTPC, Rourkela (India), Transformer- 34
Date of installation: 19/01/1994; 200MVA, 11KV /132KV; Volume of tank: 5000 litre
Concentrations of dissolved gases in ppm are shown in Table 6.

6.1 Results of sample (1) implementation:

Since transformer is degassed before sampling. Rate of TCG could not be determined. Since all gases are within limits, further diagnosis can be bypassed. There is normal ageing of transformer.

6.2 Results of sample (2) implementation:

Rate of TCG : 7.45litre /day
Rate of TCG is more than 2.8 litre/day (abnormal). Check permissible limits. Gases exceeds permissible limits. Refer DGA interpretative methods for analysis.

6.2.1. Key gas method :

Key gas C2H2 exceeds permissible limit, Fault diagnosed is Arcing.
Key gas C2H6 exceeds permissible limit, Fault diagnosed is Overheating
Key gas CO exceeds permissible limit, Fault diagnosed is Insulation Overheating

6. 2.2 Roger's Ratio method :

Actual ratios of CH4/H2, C2H6/CH4, C2H4/C2H6 & C2H2/C2H4 are 3 0.4 1 3
Codes for the ratios CH4/H2, C2H6/CH4, C2H4/C2H6 & C2H2/C2H4 are 2 0 1 2
Diagnosed fault: Fault is unidentifiable

6.2.3. Dornenburg Ratio method :

Actual ratios of CH4/H2, C2H2/C2H4,C2H2/CH4 & C2H6/C2H2 are 3 3 1.1 0.3
Fault is unidentifiable.

6.2.4 IEC method :

Actual ratios of C2H2/C2H4, CH4/H2 & C2H4/C2H6 are 3 3 1
Codes for ratios of C2H2/C2H4, CH4/H2 & C2H4/C2H6 are 1 2 1
Diagnosed fault: Fault is unidentifiable
Codes for the sample fall outside the existing IEC codes, Hence fault cannot be diagnosed. Use Proposed System for the further diagnosis.

6.2.5. Proposed diagnosis without Fuzzy :

Diagnosed fault : Winding circulating currents.

Since, Gas ratios lie on the boundary of ratio codes ,Multiple faults may occur , Refer Fuzzy Diagnostic system for the diagnosis of multiple faults

6.2.6 Fuzzy dignostic system

Mixed faults diagnosed are :
Winding circulating currents
Core circulating currents
Severity of faults : MEDIUM

6.2.7 Maintenance Suggestions :

1.Retest oil within Three months
2.Oil should be degassed
3.Check loading on the transformer
4. Check Megger for connections on bushings , leads and tap changer.
5. Check Megger for core ground test
6. Look for displaced or loose winding

Fuzzy output is given by rule viewer of FIS which is shown in Fig.7

Table 6
Concentration of dissolved gases in ppm.

Sample No.	Date of Sampling	Whether degassed ?	C_2H_2	C_2H_4	CH_4	H_2	C_2H_6	CO	CO_2
			Concentration of Gases in ppm.						
01	3/4/2007	Yes	0	11	31	43	71	353	1537
02	14/3/2008	No	243	81	210	70	81	4640	12530

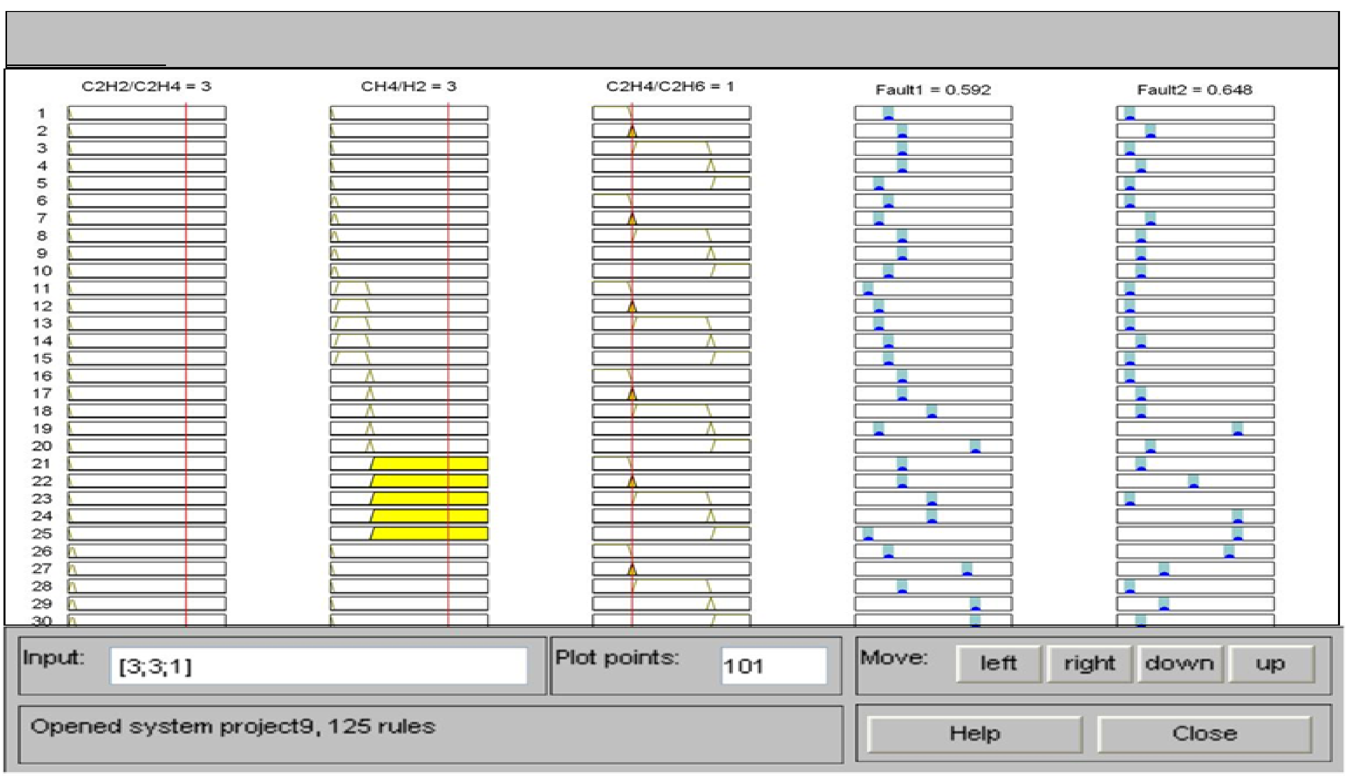

Fig.7 Rule viewer of FIS

7. Conclusion

Prototype expert system is developed on a PC using 'MATLAB'. It can diagnose the incipient faults of the suspected transformers and suggest proper maintenance actions. Fuzzy diagnosis is proposed to diagnose multiple incipient faults. Results from the implementation of the expert system shows that the number of predictions of fault is 100 % for the both Proposed Diagnosis method (with and without fuzzy). Considering number of correct prediction, IEC method has highest efficiency. But, Number of predictions by IEC method is much less than the proposed diagnosis; hence efficiency considering total number of cases is much less than Proposed Diagnosis. By using Fuzzy diagnosis, number of correct predictions is increased considerably. This work can be continued to expand the knowledge base by adding any new experience, measurement and analysis techniques.

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