FUZZY SYSTEM FOR TRANSFORMER FAULT DIAGNOSIS AND MAINTENANCE USING DGA

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Abstract: *Dissolved gas analysis (DGA) of transformer oil has been one of the most reliable techniques to detect the incipient faults. Many conventional DGA methods have been developed to interpret DGA results obtained from gas chromatography. Although these methods are widely used in the world, they sometimes fail to diagnose, especially when DGA results falls outside conventional methods codes or when more than one fault exist in transformer. To overcome these limitations, fuzzy inference system (FIS) is proposed. 200 different cases are used to test the accuracy of various DGA methods in interpreting the transformer condition .*

Key words: *DGA, Fault diagnosis, FIS, Ratio methods , Power transformer .*

1. Introduction .

The power transformer is vital equipment of the electrical power system. A transformer may function well externally with monitors, while some incipient deterioration may occur internally to cause fatal problems in later development. Nearly 80 % of faults result from incipient deteriorations. Therefore, faults should be identified and avoided at the earliest possible stage by some predictive maintenance technique. Dissolved Gas Analysis (DGA) is a reliable technique for detection of incipient faults in oil filled power transformer. It is similar to 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 working principle [1-4] is based on the dielectric breakdown of the some of the oil molecules or cellulose molecules of the insulation due to incipient faults. When there is any kind of fault, such as overheating or discharge inside the transformer, it will produce corresponding characteristic amount of gases in the transformer oil. These gases are detected at the per part million (ppm) level by Gas Chromatography [5-10]. It is a technique of separation, identification and quantification of mixtures of gases. The commonly collected and analyzed gases are Hydrogen (H_2), Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4), Ethane (C_2H_6), Carbon Monoxide (CO) and Carbon Dioxide (CO_2). Through the analysis of the concentrations of dissolved gases, their gassing rates and the ratios of certain gases, the DGA methods can determine the fault type of the transformer. Even under normal transformer operational conditions, some of these gases may be formed inside. Therefore, 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 in the transformer, concentration of gases dissolved in the oil significantly increases. A given gas volume may be generated over a long time period by a relatively insignificant fault or in a very short time period by a more severe fault. Once a suspicious gas presence is detected, it is important to be certain whether the fault that generated the gas is active by calculating the total dissolved combustible gases (TDCG) and rate of TDCG [11] which is given by Eq.(1) as follows:

$$R = \frac{(S_T - S_0).V.10^{-6}}{T} \qquad (1)$$

Where , R is rate (Liters/day) , S_o is the TDCG of First sample in ppm, S_T is the TDCG of Second sample in ppm ,V is tank oil volume in litres and T is the time (days).

The rate of generation of TDCG greater than 2.8 liters /day indicates that the transformer has an active internal fault and requires additional inspection by DGA methods.

Many interpretative methods employ an array of ratios of certain key combustible gases as the fault type indicators. These five ratios are:

R 1 = C_2H_2/ C_2H_4
R 2 = CH_4 /H_2
R 3 = C_2H_4/ C_2H_6
R 4 = C_2H_6/ C_2H_2

R 5 = C_2H_2/ C H_4

Rogers method [11-13] utilizes three ratios R1,R2 and R3.The method gives fault for the specific combination of these gas ratios. Dornenburg [11-13] utilizes four ratios R1,R2, R4andR5. This procedure requires significant levels of gases to be present for the diagnosis to be valid. The method gives fault after comparing these ratios to the limiting values.

Amongst ratio methods, IEC Standard 599 [14] is most widely used .It also utilizes three ratios R1,R2 and R3 . The coding rule and classification of faults by the IEC method are given in Tables 1 and 2.

Table 1
Coding rule for IEC method [14]

Codes	Range of gas ratios		
	R1	R2	R3
0	<0.1	0.1 - 1	<1
1	0.1 – 3	<0.1	1 - 3
2	> 3	>1	>3

Table 2
Classification of faults by IEC method [14]

Fault Type	Characteristic Fault	R1	R2	R3
1	Normal ageing (N).	0	0	0
2	Partial discharge (PD) of low energy density .	0	1	0
3	PD of high energy density.	1	1	0
4	Discharges of low energy (D1).	1-2	0	1-2
5	Discharge of high energy (D2).	1	0	2
6	Thermal fault of low temperature (TL) <150^{0}C .	0	0	1
7	TL between 150^{0}C -300 ^{0}C .	0	2	0
8	TL between 300^{0}C -700 ^{0}C.	0	2	1
9	Thermal fault of high temperature (TH) >700 ^{0}C .	0	2	2

The Duval Triangle [15-17] method utilizes three % ratios of certain gases for DGA interpretation of transformers filled with mineral oil. The triangular coordinates corresponding to DGA results in ppm can be calculated by Eqs.(2-4) as follows:

$$\%C_2H_2 = \frac{100.x}{(x+y+z)} \quad (2)$$

$$\%C_2H_4 = \frac{100.y}{(x+y+z)} \quad (3)$$

$$\%CH_4 = \frac{100.z}{(x+y+z)} \quad (4)$$

Where x, y and z are concentration of C_2H_2, C_2H_4 and C H_4 in ppm resp. In addition to these three % ratios , Xiaohui Li *et al.* ,[18] utilizes fourth % ratio which is given by Eq.(5) as follows:

$$\%H_2 = \frac{100.H_2}{(H_2 + C_2H_6 + CO + CO_2)} \quad (5)$$

All these techniques are computationally straightforward. However, these methods in some cases provide erroneous diagnoses as well as no conclusion for the fault type. To overcome these limitations, FIS is proposed.

3.Diagnostic procedure

Flow chart of proposed system diagnosis is shown in Fig.1. The input data include concentration of dissolved gases C_2H_2, C_2H_4, C_2H_6, CH_4, H_2, CO and CO_2 of the sample. Information such as tank oil volume, date of sampling and date of installation of transformer is asked for further inference.

In the first step, the system calculates TDCG and compares with the standard permissible limits [11] .For normal level of TDCG (< 720ppm), permissible limits for individual gases are checked. Normal level of TDCG and individual gases indicates the satisfactory operation of a transformer. Once an abnormal level of TDCG or individual gas has been detected, the next step is to determine the rate of generation of TDCG (1) by analysis of the successive sample. For the normal rate of TDCG (less than 2.8 liters/day), further diagnosis is bypassed. For an abnormal rate of TDCG, the proposed FIS is adopted to diagnose the probable faults. In the last step, severity degrees are assigned to the diagnosed faults. On the basis of severity of faults, appropriate maintenance actions are suggested.

4. Fuzzy inference system

Intelligent algorithms, e.g., Expert System [19], FIS[20-21], Artificial Neural Networks [22-24], Artificial Neural FIS [25-27], Wavelet Networks [28] and Combined Neural Networks And Expert System [29] have been used to interpret DGA results. These algorithms are not entirely satisfactory. These methods are mostly suitable for transformers with single fault. In case of multiple faults, only dominant fault is indicated by these methods.

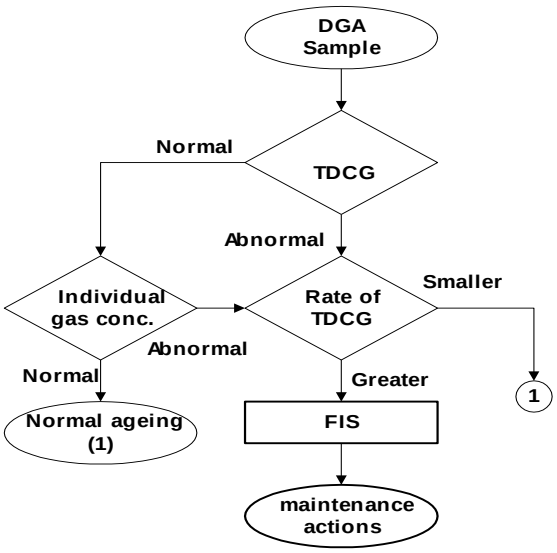

Fig. 1Flow chart of proposed system diagnosis

These methods based on specific set of codes defined for certain gas ratios. Further, no quantitative indication for severity of fault and maintenance suggestions is given by these methods.The proposed Fuzzy diagnostic method is prepared using the MATLAB Fuzzy Logic Toolbox[30]. Sugeno type FIS [31-32] is used as a fuzzy inference method.

A typical rule in the zero order Sugeno fuzzy model has the form;

If input1 = x and input2= y, then output z = constant.

The output level z of each rule is weighted by firing strength w_i of the rule. For an AND rule, firing strength is given as

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 by Eq.(6) as follows:

$$Y = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \tag{6}$$

Where ,Y is final output and N is the number of rules. The FIS consists of 3 ratios R1, R2 and R3 as inputs. One of the major drawbacks of IEC method is that when gas ratio changes across coding boundary, the code changes sharply between 0, 1 and 2. In fact the gas ratio boundary should be fuzzy. Depending on the relative values of ratios, IEC codes 0, 1 and 2 are replaced by fuzzy codes Low, Medium (Med) and High. Due to uncertainty in measurements of gas concentrations by gas analyzers, the gas ratios would have a relative uncertainty of plus or minus 10% [33]. Hence, 10% of the boundary value of each ratio (Table I) overlaps between two consecutive codes.

Membership function for code Low of ratio R1 is given by the linear declining function

$$\mu_{Low}(R1) = \begin{Bmatrix} 1 & \rightarrow R1 \le 0.09 \\ \frac{(0.11 - R1)}{(0.11 - 0.09)} & 0.09 \le R1 \le 0.11 \\ 0 & R1 \ge 0.11 \end{Bmatrix} \tag{7}$$

Membership function for code Med of ratio R1 is given by trapezoidal function

$$\mu_{Med}(R1) = \begin{Bmatrix} 0 & \rightarrow R1 \le 0.09 \\ \frac{(R1 - 0.09)}{(0.11 - 0.09)} & \rightarrow 0.09 \le R1 \le 0.11 \\ 1 & 0.11 \le R1 \le 2.7 \\ \frac{(3.3 - R1)}{(3.3 - 2.7)} & 2.7 \le R1 \le 3.3 \\ 0 & R1 \ge 3.3 \end{Bmatrix} \tag{8}$$

Membership function for code High of ratio R1 is given by linear increasing function

$$\mu_{High}(R1) = \begin{Bmatrix} 0 & \rightarrow R1 \le 2.7 \\ \frac{(R1 - 2.7)}{(3.3 - 2.7)} & \rightarrow 2.7 \le R1 \le 3.3 \\ 1 & R1 \ge 3.3 \end{Bmatrix} \tag{9}$$

The codes of the ratios R2 and R3 are also fuzzified as Low , Med and High variable depending on the range of ratios for these codes . Membership function for ratio R3 is shown in Fig.2. The FIS comprises of single output which has 5 fault types as membership functions. Weight in the range of 0 to 1 is assigned to each fault type on the basis of severity of the fault. The five types of faults used in FIS are TL < 0.2 >, PD < 0.4 >, D1 < 0.6 >, TH < 0.8 > and D2 < 1.0 >.

The major drawback of the IEC method is that a significant number of DGA results in- service fall outside the existing rules and cannot be diagnosed. Only 11 inference rules are suggested by the IEC (Table II) out of the 27 (3x3x3) possible rules. To overcome this limitation, existing 11rules are modified in terms of fuzzy variables and additional 16 new rules are obtained as a result of extensive consultations with utility experts, existing literature, and approximately 1500 DGA case histories. Each rule consists of two components which are the antecedent (IF part) and the consequent (THEN part). The rules having a similar output are clubbed together and kept in order of increasing value of the weight of the fault. The fuzzy rules are given below:

Rule 1: IF R1 =Low AND R2=Low AND R3=Med, THEN Fault=TL.
Rule 2: IF R1 =Low AND R2=Med AND R3=Low, THEN Fault=TL.
Rule 3: IF R1 =Low AND R2=Med AND R3=Med, THEN Fault=TL.

FIS derives output from judging all the fuzzy rules by finding the weighted average of all 27 fuzzy rules output.

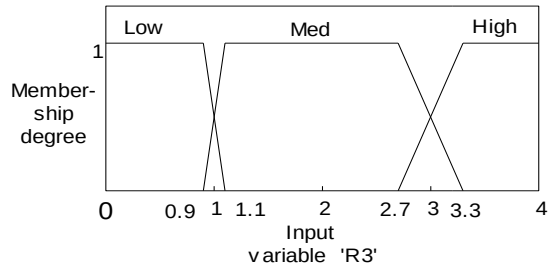

Fig.2 Membership function for ratio R3

5. Case studies, results and discussions

FIS is developed based on the proposed interpretative rules and diagnostic procedure of an overall system. To demonstrate the feasibility of the system in diagnostic, 200 DGA gas records supplied by the major power companies in India have been tested.

Accuracy is calculated in two different ways,

a) When considering only number of predictions, percentage accuracy is given by Eq. (10) as follows:

$$A_P = \frac{100.T_R}{T_P} \tag{10}$$

Where T_R is the number of correct predictions and T_P is the total number of the predictions,

b) When considering the total number of cases, percentage accuracy is given in Eq. (11) as follows :

$$A_C = \frac{100.T_R}{T_C} \tag{11}$$

Where Tc is the total number of cases.

Accuracy values of different methods for total 200 cases are compared and summarized in Table 3. Results from two case studies are presented here.

5.1 Case Study- I

A 40MVA, 220KV /11KV transformer is in service for 23 yrs.. Tank oil volume is 28000 liters. This transformer had overheated off circuit tapping switching contacts.DGA data obtained in ppm after the fault on 11/06/2010 is as follows:

Table 3
Comparison of accuracy of different methods

Method	T_R	T_P	A_P	A_C
Doernenburg	77	111	69.37	38.50
Roger	89	145	61.38	44.50
IEC	142	170	83.53	71.00
Duval Triangle	172	200	86.00	86.00
Xiaohui Li *et al.*	181	200	90.50	90.50
Proposed Method	187	200	93.50	93.50

C_2H_2-31 ; C_2H_4-53 ; CH_4-304; H_2-163; C_2H_6-15; CO-524; CO_2-786.

Step 1: TDCG in ppm =1090. TDCG is above normal (> 720 ppm).

Step 2: The transformer is sampled again on 14/06/2010 to determine rate of TDCG.. Concentrations of dissolved gases in ppm are as follows: C_2H_2-34; C_2H_4-69; CH_4-353; H_2-197; C_2H_6-22; CO-618; CO_2- 931.

TDCG in ppm = 1292; Rate of TDCG = 18.85 lit/day, which is greater than normal level (2.8lit/day).

Step 3: FIS is applied for fault diagnosis. The output of FIS is given by rule viewer which is shown in Fig.3. Rule viewer shows R1=0.493 (Med), R2=1.79(High) and R3=3.14 which lies on the boundary of the fuzzy ratios Med and High. Dark dots in the fault column show that rules 7 and 22 are satisfied which indicate possible faults TL and TH resp. This result matches with the actual fault of the transformer. Weighted average of both the rules is given as 0.636.Weight of both the faults can be calculated as follows:

Weight of TL = (0.8 - 0.636) / (0.8 - 0.2) = 0.273
Weight of PD =1-0.273 = 0.727
The weights point towards the strong possibility of fault TH and the relatively less possibility of fault TL.

Step4: Severity of faults is High. Maintenance actions suggested are as follows:

1. Observe extreme caution
2. Retest oil weekly.
3. Plan outage .

5.2 Case Study- II

A 25 MVA, 220KV /132KV transformer is in service for 15 yrs.. Tank oil volume is 20000 liters. This transformer had an X - wax deposition.

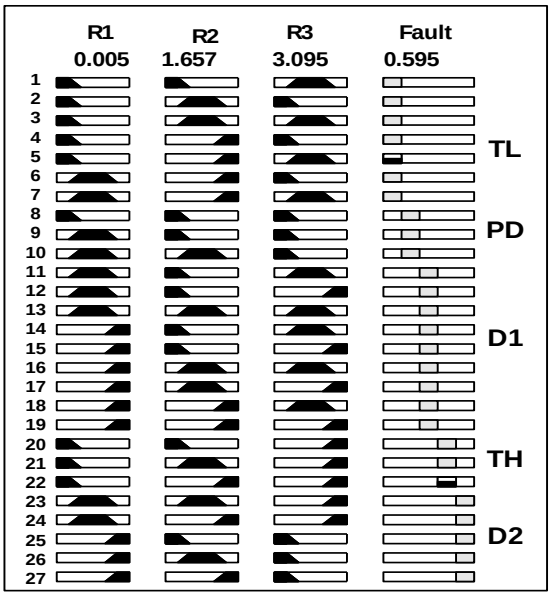

Fig.3 Rule viewer for Case-II

Traces of discharges were found on paper of high voltage cable.DGA data obtained in ppm after the fault on 18/03/2009 is as follows:

C_2H_2-15 ; C_2H_4-19 ; CH_4-172; H_2-1903; C_2H_6-14; CO-180; CO_2-635.

Step 1: TDCG in ppm =2303. TDCG is above normal (> 720 ppm).

Step 2: The transformer is sampled again on 21/03/2009 to determine rate of TDCG.. Concentrations of dissolved gases in ppm are as follows: C_2H_2-26 C_2H_4-23; CH_4-2221; H_2-2257; C_2H_6-22; CO-220; CO_2- 821.

TDCG in ppm = 2769; Rate of TDCG = 3.10 lit/day, which is greater than normal level (2.8lit/day).

Step 3: FIS is applied for fault diagnosis. The output of FIS is given by rule viewer which is shown in Fig.4 Rule viewer shows R1=1.13 (Med), R2=0.0979 which lies on the boundary of the fuzzy ratios Low and Med and R3=1.05 which lies on the boundary of the fuzzy ratios Low and Med. Dark dots in the fault column show that the rules 9,10,11 and 13 are satisfied which indicate possible faults PD and D1. This result matches with the actual fault of the transformer. Weighted average of both the rules is given as 0.529.Weight of both the faults can be calculated as follows:

Weight of PD = (0.6 - 0.529) / (0.6- 0.4) = 0.355
Weight of D1 =1-0.355 = 0.645
The weights point towards the strong possibility of fault D1 and the relatively less possibility of fault PD.

Step4: Severity of faults is Medium. Maintenance actions suggested are as follows:

1. Observe caution
2. Retest oil monthly.
3. Determine load dependence.

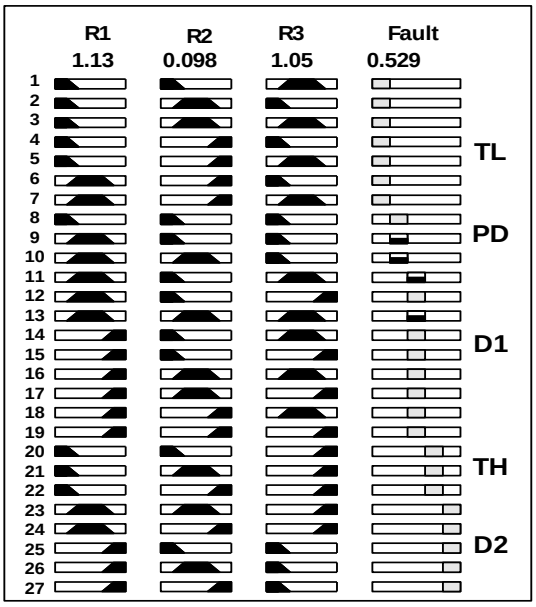

Fig.4 Rule viewer for Case-III

6. Conclusion

The proposed FIS is developed using 'MATLAB'. It can diagnose the incipient faults of the suspected transformers and suggest proper maintenance actions. The fuzzy three ratio method is proposed to diagnose multiple faults and faults that cannot be diagnosed by the conventional DGA methods. Proposed FIS provides fault diagnosis for all the cases. An accuracy of the proposed method is better than other diagnostic methods.

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