# Fuzzy Logic Application in DGA Methods to Classify Types of Faults in Oil Transformer

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*Abstract*— **Assessment of power transformer conditions is increasing concern in latest years. Dissolved gas in oil analysis (DGA) is successful technique and provided wealth of diagnostic information to detect incipient faults in power transformer. This paper used two methods developed to interpret DGA results which are Rogers Ratio and IEC Ratio. However, there are situations of errors and misleading results occurring due to borderline and multiple faults. Fuzzy logic is described and implemented as an improved DGA interpretation method that provides higher reliability and precision of fault diagnostics.**

***Keywords-fault diagnosis of transformer; DGA methods; Fuzzy Logic***

## I. INTRODUCTION

Power transformers are the most critical and expensive equipments in electrical power systems and their failure can cause interruptions in the supply to electric installations. Increasing concern in assessment of power transformer conditions to diagnostic incipient faults will reduce the danger to the installation and minimized the overall cost.

Faults in oil insulator of transformer occur due to electrical and thermal stresses [1]. In addition, gases at various concentrations may be released and dissolved in the oil. The distribution of these gases can be related to the type of electrical fault and the rate of gas generation can indicate the severity of the fault. The fault gases dissolved in transformer oil are hydrogen ($H_2$), methane ($CH_4$), ethane ($C_2H_6$), ethylene ($C_2H_4$), acetylene ($C_2H_2$), carbon monoxide (CO) and carbon dioxide ($CO_2$).

There are several techniques in detecting those fault gases and DGA was recognized as the most effective method. Currently, there are various methods developed to do the interpretation of the fault type from the DGA data. In this paper, the two methods of the interpretation of the fault gases are investigated which are Rogers Ratio and IEC Ratio.

Although DGA has widely been used in the industry, in some cases, the conventional methods fail to diagnosis. This normally happens for those transformers which have multiple types of fault. Actually, the conventional diagnostic methods are based on the ratio of gases generated from a single fault or from multiple faults but with one of dominant nature in transformer. When gases from more than one fault in a transformer are collected, the relation between different gases becomes too complicated which may not match the codes are pre-defined [2]. Fuzzy Logic is used to diagnose multiple faults in transformer.

Fuzzy Logic provides an approximate but effective means of describing the behavior of system that are too complex or not easily analyzed [3]. The final diagnosis rules are automatically determined and the membership functions of the corresponding fuzzy subsets are simultaneously adjusted [4]. In this paper, Fuzzy Logic controller was developed using MATLAB to automate evaluation of both methods. Results obtained from the experiment revealed that Fuzzy technique is a feasible approach in addressing fault classification in a transformer.

## II. METHODOLOGY

### *A. Fault Gas Analysis*

Mineral oil functions as a cooler of transformer and provides insulation as well. When mineral oil is subjected to high thermal and electrical stresses, it decomposes and as a result, gases are generated. These gases are considered as fault indicators and can be generated in certain patterns and amounts depending on the characteristics of the fault [5].

Dissolved gas in oil analysis (DGA) is a sensitive and reliable technique to diagnostic the incipient and potential faults in power transformer. By using this technique, it is possible to distinguish fault in a great variety of oil filled equipment. Table I tabulates the fault type addressed in this paper.

TABLE I
FAULT TYPE USED IN ANALYSIS

| Fault Type | Fault Type Code |
|---|---|
| Thermal fault at low temperature | TF |
| Overheating and sparking | OH |
| Arching | ARC |
| Partial Discharge and Corona | PD |
| Normal | normal |

### *B. DGA Interpretation Method*

There are many methods in DGA. The ratio methods are the most widely used technique. In this paper two of the ratio methods are studied which are Roger's Ratio and IEC Ratio. Each diagnosis method was grouped according to the faults type code. This is tabulated in Table II [4].

TABLE II
GROUPING FOR FAULT TYPE CODES [4]

| Method | TF | OH | ARC | PD | Normal |
|---|---|---|---|---|---|
| Roger | Slight overheating <150°C<br><br>Overheating 150°C-200°C<br><br>Overheating 200°C-300°C | Conductor overheating<br><br>Winding circulating current<br><br>Core/tank circulating current | Flashover<br><br>Arching<br><br>Continuous sparking | PDs<br><br>PDs with tracking | Normal |
| IEC | Thermal fault <150°C<br><br>Thermal fault 150°C-300°C | Thermal fault 300°C-700°C<br><br>Thermal fault >700°C | Discharge of low energy<br><br>Discharge of high energy | PDs of low energy density<br><br>PDs of high energy density | Normal |

#### *i. Roger's Ratio*

The Roger's method utilizes four gas ratios. Diagnosis of faults is accomplished via a simple coding scheme based on ranges of the ratios as tabulated in Table III and IV [6].

TABLE III
GAS RATIO CODES [6]

| Gas ratios | Ratio codes |
|---|---|
| $CH_4/H_2$ | i |
| $C_2H_6/CH_4$ | j |
| $C_2H_4/C_2H_6$ | k |
| $C_2H_2/C_2H_4$ | l |

TABLE IV
ROGER'S RATIO CODES [6]

| Ratio code | Range | Code |
|---|---|---|
| i | $x < 0.1$<br>$0.1 \leq x \leq 1.0$<br>$1.0 \leq x \leq 3.0$<br>$x > 3.0$ | 5<br>0<br>1<br>2 |
| j | $x < 1.0$<br>$x \geq 1.0$ | 0<br>1 |
| k | $x < 1.0$<br>$1.0 \leq x \leq 3.0$<br>$x > 3.0$ | 0<br>1<br>2 |
| l | $x < 0.1$<br>$0.1 \leq x \leq 3.0$<br>$x > 3.0$ | 0<br>1<br>2 |

TABLE V
CLASSIFICATION OF FAULT BASED ON ROGER'S RATIO CODES [6]

| i | j | k | l | Diagnosis | |
|---|---|---|---|---|---|
| 1-2 | 0 | 0 | 0 | Slight overheating <150°C | TF_1 |
| 1-2 | 1 | 0 | 0 | Overheating 150°C-200°C | TF_2 |
| 0 | 1 | 0 | 0 | Overheating 200°C-300°C | TF_3 |
| 0 | 0 | 1 | 0 | Conductor overheating | OH_1 |
| 1 | 0 | 1 | 0 | Winding circulating currents | OH_2 |
| 1 | 0 | 2 | 0 | Core/tank circulating currents, overhead joints | OH_3 |
| 0 | 0 | 0 | 1 | Flashover without power follow through | ARC_1 |
| 0 | 0 | 1-2 | 1-2 | Arc with power follow through | ARC_2 |
| 0 | 0 | 2 | 2 | Continuous sparking to floating potential | ARC_3 |
| 5 | 0 | 0 | 0 | Partial discharge | PD_1 |
| 5 | 0 | 0 | 1-2 | Partial discharge with tracking (note CO) | PD_2 |
| 0 | 0 | 0 | 0 | Normal deterioration | normal |

#### *ii. IEC Ratio*

This method originated from the Roger's Ratio method, except that the ratio $C_2H_6/CH_4$ was dropped since it only indicated a limited temperature range of decomposition [4]. The three gas ratios with different code as compared to the Roger's Ratio method that tabulated in Table VI [6].

TABLE VI
IEC RATIO CODES [6]

| Ratio code | Range | Code |
|---|---|---|
| l | $x < 0.1$<br>$0.1 \leq x \leq 3.0$<br>$x > 3.0$ | 0<br>1<br>2 |
| i | $x < 0.1$<br>$0.1 \leq x \leq 1.0$<br>$x > 1.0$ | 1<br>0<br>2 |
| k | $x < 1.0$<br>$1.0 \leq x \leq 3.0$<br>$x > 3.0$ | 0<br>1<br>2 |

TABLE VII
CLASSIFICATION OF FAULT BASED ON IEC RATIO [6]

| l | i | k | Diagnosis | |
|---|---|---|---|---|
| 0 | 0 | 1 | Thermal fault <150°C | TF_1 |
| 0 | 2 | 0 | Thermal fault 150°C-300°C | TF_2 |
| 0 | 2 | 1 | Thermal fault 300°C-700°C | OH_1 |
| 0 | 2 | 2 | Thermal fault >700°C | OH_2 |
| 1-2 | 0 | 1-2 | Discharge of low energy | ARC_1 |
| 1 | 0 | 2 | Discharge of high energy | ARC_2 |
| 0 | 1 | 0 | PDs of low energy density | PD_1 |
| 1 | 1 | 0 | PDs of high energy density | PD_2 |
| 0 | 0 | 0 | Normal | normal |

Although Roger's Ratio and IEC Ratio are useful for transformer insulation, no quantitative criterion is provided for possibility of occurrence of each fault. Also, in some cases, the DGA result cannot match by the existing codes making the diagnosis is unsuccessful. In multiple fault conditions, the gases from different faults are mixed together resulting in confusing ratios between different gas components [2]. This can be overcome by the aid of fuzzy diagnosis as presented in this paper. The fault types listed in Table V and Table VII form the fuzzy rule set for the diagnosis system to be covered in the next section.

### C. *Fuzzy Logic Application*

The fuzzy analysis consists of three operations which are fuzzification, fuzzy inference and defuzzification. Fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. A chosen fuzzy inference system (FIS) is responsible for drawing conclusions from the knowledge-based fuzzy rule set of if-then linguistic statements. Defuzzification then converts the fuzzy output values back into crisp output actions.

#### i. *Fuzzy Roger's Ratio*

As shown in Table IV, the four ratio codes are defined as inputs and classified as either Low (Lo), Medium (Med), High (Hi) and Very High (Vhi) [4]. Table VIII shows the membership intervals of each ratio.

TABLE VIII
MEMBERSHIP INTERVALS FOR ROGER'S RATIO

| Ratio code | Range | Code |
|---|---|---|
| i | $x < 0.1$ | 5 (Lo) |
| | $0.1 \leq x \leq 1.0$ | 0 (Med) |
| | $1.0 \leq x \leq 3.0$ | 1 (Hi) |
| | $x > 3.0$ | 2 (Vhi) |
| j | $x < 1.0$ | 0 (Lo) |
| | $x \geq 1.0$ | 1 (Hi) |
| k | $x < 1.0$ | 0 (Lo) |
| | $1.0 \leq x \leq 3.0$ | 1 (Med) |
| | $x > 3.0$ | 2 (Hi) |
| l | $x < 0.1$ | 0 (Lo) |
| | $0.1 \leq x \leq 3.0$ | 1 (Med) |
| | $x > 3.0$ | 2 (Hi) |

The membership boundaries are fuzzified represented by a trapezoidal fuzzy-membership function illustrated in Figure 1 for ratio code i, j, k and l.

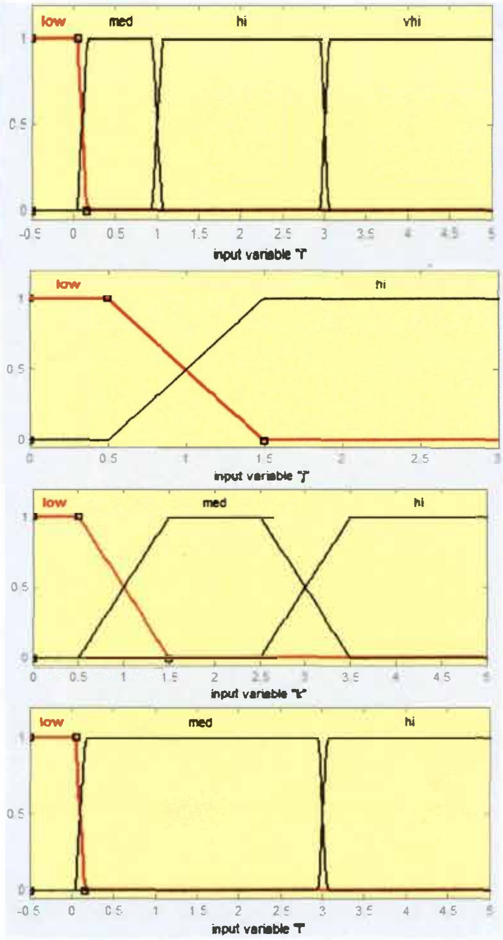

Fig. 1 Membership function of ratio code i, j, k and l

Fuzzy inference uses IF-THEN rule-based system, given by, IF antecedent and THEN consequent. Here, a fuzzy rule set is then used to form judgement on the fuzzy inputs derived from the 4 gas ratios. 18 fuzzy rules can be derived and there are some examples of the fuzzy rules based on the fault types listed in Table V:

*Rules 1: IF i is high AND j is low AND k is low AND l is low THEN Faults is TF_1* (1)

*Rules 6: IF i is medium AND j is low AND k is medium AND l is low THEN Faults is OH_1* (2)

When fuzzy rule has multiple antecedents, the fuzzy operator AND for minimization operator and OR for maximization operator is used to obtain a single number that represents the result of the antecedent evaluation. Therefore, the following equations are produced based on Roger's Ratio rules to diagnose different fault:

*Fault(TF_1) = max{ min[i=Hi, j=Lo, k=Lo, l=Lo], min[i=Vhi, j=Lo, k=Lo, l=Lo]}* (3)

*Fault(OH_1) = min[i=Med, j=Lo, k=Med, l=Lo]* (4)

Although the fuzzy rules appear strictly defined, borderline cases with gas ratio on or near the line between linguistic values (low, medium, high and very high) allows Fuzzy Inference System (FIS) to interpret membership of these rules flexibly and classify these cases under two different fault types with individual probability of occurrence attached to each type [3].

Fuzzy Inference System (FIS) involves the operations between input fuzzy sets, as illustrated graphically in Figure 2. It is based on fuzzy inference that describe previously. As illustrated in Figure 2, each rule is a row of plots and each column is a variable. The first four columns of plots (yellow) show the membership functions referenced by the antecedent, or the if-part of each rule. The fifth column of plots (blue) shows the membership functions referenced by the consequent, or the then-part of each rule.

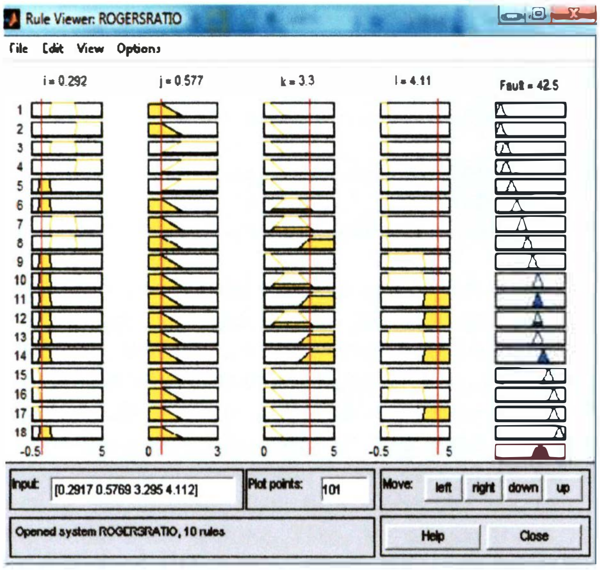


Fig. 2 FIS analysis

*ii. Fuzzy IEC Ratio*

The three gas ratio codes are defined as inputs and classified as either Low (Lo), Medium (Med) and High (Hi) according to membership intervals as tabulated in Table IX:

TABLE IX
MEMBERSHIP INTERVALS FOR IEC RATIO

| Ratio code | Range | Code |
|---|---|---|
| l | $x < 0.1$<br>$0.1 \le x \le 3.0$<br>$x > 3.0$ | 0 (Lo)<br>1 (Med)<br>2 (Hi) |
| i | $x < 0.1$<br>$0.1 \le x \le 1.0$<br>$x > 1.0$ | 1 (Lo)<br>0 (Med)<br>2 (Hi) |
| k | $x < 1.0$<br>$1.0 \le x \le 3.0$<br>$x > 3.0$ | 0 (Lo)<br>1 (Med)<br>2 (Hi) |

Figure 3 is the fuzzy membership function for this method:

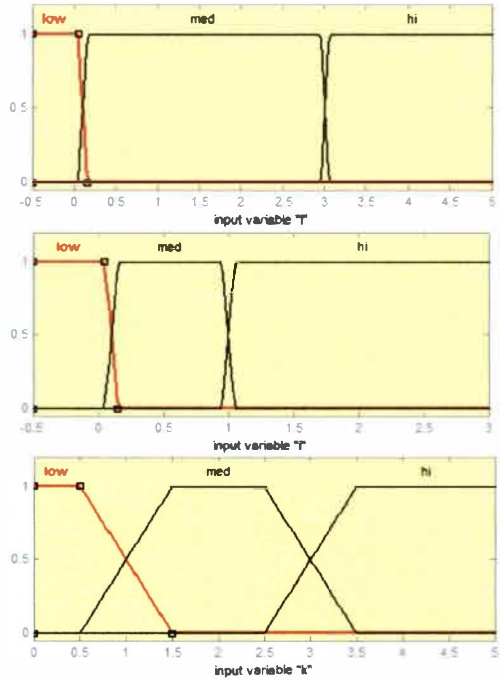


Fig. 3 Membership function of ratio code I, i and k

12 fuzzy rules can be defined based on the fault types listed in Table VI. The fuzzy analysis of this method was developed using the same technique as described in the previous method.

## III. Results And Discussion

In order to evaluate the performance of fuzzy logic to classify the fault types of the transformer, 15 oil samples are used and tabulated in Table X [7].

TABLE X
DGA SAMLPES [7]

| No. | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ |
|---|---|---|---|---|---|
| 1 | 200 | 700 | 250 | 740 | 1 |
| 2 | 56 | 61 | 75 | 32 | 31 |
| 3 | 33 | 26 | 6 | 5.3 | 0.2 |
| 4 | 176 | 205.9 | 47.7 | 75.7 | 68.7 |
| 5 | 70.4 | 69.5 | 28.9 | 241.2 | 10.4 |
| 6 | 345 | 112.25 | 27.5 | 51.5 | 58.75 |
| 7 | 172.9 | 334.1 | 172.9 | 812.5 | 37.7 |
| 8 | 2587.2 | 7.882 | 4.704 | 1.4 | 0 |
| 9 | 1678 | 652.9 | 80.7 | 1005.9 | 419.1 |
| 10 | 206 | 198.9 | 74 | 612.7 | 15.1 |
| 11 | 180 | 175 | 75 | 50 | 4 |
| 12 | 106 | 24 | 4 | 28 | 37 |
| 13 | 180.85 | 0.574 | 0.234 | 0.188 | 0 |
| 14 | 27 | 90 | 24 | 63 | 0.2 |
| 15 | 138.8 | 52.2 | 6.77 | 62.8 | 9.55 |

TABLE XI
COMPARISON BETWEEN ACTUAL FAULT AND DIAGNOSIS RESULT BY ROGER'S RATIO METHOD AND IEC RATIO METHOD

| **No.** | **Actual fault** | **Diagnosis using Fuzzy Logic** | | | |
|---|---|---|---|---|---|
| | | **Roger's Ratio** | **Fault classification** | **IEC Ratio** | **Fault classification** |
| 1 | Overheating and sparking | 2010 | Overheating and sparking | 021 | Overheating and sparking |
| 2 | Partial Discharge and Corona | 1101 | Overheating and sparking* | 120 | Arching* |
| 3 | Normal | 0000 | Normal | 000 | Normal |
| 4 | Arching | 1011 | Overheating and sparking* | 121 | Arching |
| 5 | Overheating and sparking | 0020 | Overheating and sparking | 002 | Overheating and sparking |
| 6 | Arching | 0011 | Arching | 101 | Arching |
| 7 | Overheating and sparking | 1020 | Overheating and sparking | 022 | Overheating and sparking |
| 8 | Partial Discharge and Corona | 5000 | Partial Discharge and Corona | 010 | Partial Discharge and Corona |
| 9 | Arching | 0021 | Arching | 102 | Arching |
| 10 | Overheating and sparking | 0020 | Overheating and sparking | 002 | Overheating and sparking |
| 11 | Thermal fault at low temperature | 0000 | Normal* | 000 | Normal* |
| 12 | Arching | 0021 | Arching | 202 | Arching |
| 13 | Partial Discharge and Corona | 5000 | Partial Discharge and Corona | 010 | Partial Discharge and Corona |
| 14 | Overheating and sparking | 2010 | Overheating and sparking | 021 | Overheating and sparking |
| 15 | Arching | 0021 | Arching | 102 | Arching |

Note: *no corresponding with actual result

The results of detected fault for each DGA method is classified in their own fault type as tabulated in Table XI. From the table, the results between the actual inspection of transformer and DGA methods diagnosis using fuzzy logic are approximately the same. In sample 4, Roger's Ratio with the aid of fuzzy logic managed to detect the core/tank circulating current and overhead joints fault classified as overheating and sparking fault type which did not match with the actual fault, arching. Then, for sample 2 and 11, both DGA methods fail to fit the actual fault evaluated using fuzzy logic. The reason could cause by the inaccuracy of gas concentration data during the measurement of oil samples.

Table XI tabulates actual fault and result of type of faults for each oil sample using both DGA methods, Roger's Ratio and IEC Ratio by applying the fuzzy logic. The results between the actual inspection of transformer and DGA methods diagnosis using fuzzy logic are approximately the same. In some samples, both DGA methods with applying fuzzy logic fail to fit the actual fault. The reasons are unclear. With the cumulating of the experience, the accuracy of diagnosis will be increased. From the result obtained, it is proved that by applying the fuzzy logic, the incipient fault can be defined and classified effectively.

TABLE XII
RESULT ANALYSIS FOR EACH TYPE OF FAULTS

| Method | Fault code | Number of cases | Number of correct prediction | % Successful prediction (S) | Consistency (C) |
|---|---|---|---|---|---|
| Roger | TF | 1 | 0 | 0% | 23% |
| | OH | 5 | 5 | 100% | |
| | ARC | 5 | 4 | 80% | |
| | PD | 3 | 2 | 67% | |
| | normal | 1 | 1 | 100% | |
| IEC | TF | 1 | 0 | 0% | 24% |
| | OH | 5 | 5 | 100% | |
| | ARC | 5 | 5 | 100% | |
| | PD | 3 | 2 | 67% | |
| | normal | 1 | 1 | 100% | |

The percentage of successful prediction and consistency are calculated using the following formulas and the result presented in Table XII:

$$S = \frac{Number\ of\ correct\ prediction}{Number\ of\ cases} \times 100 \quad (5)$$

$$C = \frac{\sum Sn}{Number\ of\ fault\ type} \times 100 \quad (6)$$

Where:

n = fault type code

There are several methods has been developed to interpret DGA results. For system without fuzzy logic, methods which take into account the limit value of fault gases before doing diagnosis such as Duval Triangle, Key Gas, Nomograph and Doernenburg have better success in predicting the normal condition. For Roger's Ratio and IEC Ratio that have no limit values of fault gases always fail to predict the normal condition which affect the consistency result. It is the reason of the consistency of both methods is small. From the table, it is found that the IEC Ratio is more consistent compared to Roger's Ratio with consistency of 24% which calculate from the equation 2.

It was also found that by applying fuzzy logic, the Roger's Ratio and IEC Ratio are 100% successfully predicting the fault type OH and normal. The IRC Ratio is also the best method for predicting fault type ARC.

In addition to consistency, the accuracy of each method is another parameter used for comparison. The accuracy of each method is calculated using the following formula:

$$A = \frac{Tr}{Ts} \times 100 \tag{7}$$

Where:

Ts = Total samples

Tr = Correct predictions

TABLE XIII
COMPARISON OF ACCURACY VALUES

| Method | Total samples, Ts | Correct prediction, Trr | Incorrect prediction, Tw | % accuracy |
|---|---|---|---|---|
| Roger | 15 | 12 | 3 | 80% |
| IEC | 15 | 13 | 2 | 87% |

The results are summarized in Table XIII. It is observed that Roger's Ratio with fuzzy logic made correct diagnosis in 12 samples out of 15 and IEC Ratio with fuzzy logic made correct diagnosis 13 of the 15 samples. Based on this observation, the accuracy of each method could be determined. Roger's Ratio and IEC Ratio present 80% and 87% accuracy respectively. This indicates that the IEC Ratio method is 7% more accurate compared to Roger's Ratio method in classifying the fault type in oil transformers.

## IV. Conclusions

In this paper, two methods have been applied for the interpretation of fault types from the DGA data namely Roger's Ratio and IEC Ratio. Fuzzy logic was explored to improve the diagnosis technique. Furthermore, it has been proved that by using fuzzy logic, the fault type of transformer can be obtained efficiently. Fuzzy logic is applied as the practical representation of the relationship between the fault type and the dissolved levels with fuzzy membership functions. Multiple faults can also be diagnosed by applying fuzzy logic approach. By applying fuzzy logic in DGA methods the lifespan of transformer can be increased while the cost of maintenance can be reduced accordingly. In order to increase the accuracy of this method, more transformer samples should be analyzed in comparison with actual fault. In addition, appropriate membership functions and rules are necessary to obtain acceptable accuracy.

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