Abstract— Dissolved gas analysis (DGA) of transformer oil is one of the most effective power transformer condition monitoring tools. There are many interpretation techniques for DGA results. However, all of these techniques rely on personnel experience more than standard mathematical formulation. As a result, various DGA interpretation techniques do not necessarily lead to the same conclusion for the same oil sample. DGA interpretation is yet a challenge in the power transformer condition monitoring research area. To alleviate this issue, this paper introduces a fuzzy logic approach to help in standardizing DGA results quantification and classification using various interpretation techniques such as key gas, Rogers ratio, IEC ratio, Doernenburg and Duval triangle methods. In this context, DGA results for 2000 oil samples have been collected from different transformers of different ratings, life span and operating conditions. Traditional DGA interpretation techniques are used to analyze the results which are then compared with the results of the fuzzy logic models. Results show that the fuzzy logic models enhance the consistency among all current interpretation techniques and can eliminate the need for expert personal to interpret DGA results.

Index Terms— Transformer Diagnosis, Condition monitoring, DGA, Fuzzy Logic.

I. INTRODUCTION

POWER transformers are vital links in any transmission and distribution network. Monitoring and diagnostic techniques are essential to decrease maintenance and to improve reliability of the equipment. Currently there are several chemical and electrical diagnostic techniques applied for power transformers [1]. The electrical windings in a power transformer consist of paper insulation immersed in insulating oil, hence transformer oil and paper insulation are essential sources to detect incipient faults, fast developing faults, insulation trending and generally reflects the health condition of the transformer. During faults and due to electrical and thermal stresses that in-service transformer exhibits, oil and paper decomposition occurs evolving gases that will decrease the heat dissipation capability and the dielectric strength of the oil [2]. Gases produced due to oil decompositions are hydrogen (H₂), methane (CH₄), acetylene (C₂H₂), ethylene (C₂H₄) and ethane (C₂H₆). On the other hand paper decomposition produces carbon monoxide (CO) and carbon dioxide (CO₂) [2]. Transformer oil dissolved gas analysis (DGA) is widely used to detect incipient faults and it can be used to determine the transformer failure rank [3]. There are many DGA interpretation techniques such as key gas method [4], Doernenburg, IEC and Rogers ratio methods [5, 6] and Duval triangle method [7] have been reported in the literatures. However, all of these methods rely on personnel experience more than mathematical formulation and they do not necessarily lead to the same conclusion for the same oil sample. Precise DGA interpretation is yet a challenge in the power transformer condition monitoring research area. Availability of DGA data history has recently motivated researchers to develop a standard technique for DGA interpretation based on mathematical techniques [8-13]. Transformer internal faults are divided into thermal and electrical categories. Each fault category evolves particular characteristic gases. However, the analysis is not always straightforward as there may be more than one fault present at the same time. From the type and amount of gas, the fault nature can be determined. Various faults produce energy from low level to very high level sustained arcing. The low level energy is a partial discharge, which produces H₂ and CH₄. The arcing is capable of generating all gases including C₂H₂ [2]. Except for CO and CO₂, all other gases are formed due to the decomposition of oil. CO and CO₂ in DGA represent a good source for paper monitoring. Presence of C₂H₂ in the oil is an indication of high energy arcing.

II. FUZZY LOGIC MODELS

In this section, fuzzy logic models are developed to aid in standardizing the results of various DGA interpretation techniques. Each fuzzy logic model is developed in accordance to fuzzy inference flow chart shown in Fig. 1. Input variables to the model are the 7-key gases in particle per million (ppm). The output of the each model is divided into 6 sets covering all fault conditions that a transformer may exhibit in addition to a normal condition (F5) and out of code (F6) for ratio methods as summarised in table I. The output membership functions for all models is shown in Fig. 2.
Each model is built using the graphical user interface tools provided by MATLAB. Each input was fuzzified into various sets (normal to significant) of triangular combination membership functions (MF).

### TABLE I

<table>
<thead>
<tr>
<th>Method</th>
<th>Faults</th>
<th>F3</th>
<th>F4</th>
<th>F6</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key gas</td>
<td>Over heated oil</td>
<td>Arcing in oilPDs</td>
<td>Out of code</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Roger</td>
<td>Thermal Fault &lt;150°C</td>
<td>Partial Discharge</td>
<td>Out of code</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Fault between 150-300°C</td>
<td>High energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Fault between 300-700°C</td>
<td>Continues Sparking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Fault &gt;700°C</td>
<td>Discharge of high energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doernenburg</td>
<td>Thermal Decomposition</td>
<td>Arcing/Corona Corona</td>
<td>Out of code</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Duval Triangle</td>
<td>Hot spot &lt;200°C</td>
<td>Corona discharge</td>
<td>Out of code</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hot spot between 200-700°C</td>
<td>High Energy Arcing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hot spot &gt;400°C</td>
<td>Low Energy Arcing</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

A set of fuzzy logic rules in the form of (IF-AND-THEN) statements relating the input to the output variables was developed based on transformer’s diagnostic and test data interpretation techniques as is elaborated in the following section.

### III. FUZZY LOGIC MODELS FOR VARIOUS DGA METHODS

#### A. Key Gas Method

Membership functions for input variables are established based on the amount of gases present in oil. Set of fuzzy rules relates the input variables to the output variables are developed based on transformer’s diagnostic and test data interpretation techniques as shown in Fig. 3. The model is tested with inputs, H₂ (75 ppm), CH₄ (75 ppm), C₂H₆ (50 ppm), C₂H₄ (50 ppm), CO (200 ppm) and CO₂ (1500 ppm) as detected in one of the transformer oil samples results using DGA. The model output is 5 as shown in Fig. 3. This is corresponding to F2 (thermal) fault as can be seen from Table I and Fig. 2. This is attributed to the high level of C₂H₂ and the critical level of C₂H₄.

![](image)

**Fig. 3. Key gas Fuzzy rules**

#### B. Doernenburg Method

Set of fuzzy rules relates the input and the output variables are developed for this method as shown in Fig. 4. The model is tested with inputs, CH₄/H₂ (1), C₂H₂/C₂H₄ (0.1), C₂H₆/C₂H₂ (0.5), C₂H₂/CH₄ (1) as detected in one of the transformer oil samples DGA results. Fuzzy logic model output is 1, which is corresponding to F5 (normal condition).

#### C. Duval Triangle fuzzy logic

Set of fuzzy rules relates the input to the output variables is developed for this method as shown in Fig. 5. The model is tested with inputs, CH₄/(C₂H₂+C₂H₄+CH₄) (43.3%), C₂H₆/(C₂H₂+C₂H₄+CH₄) (80.1%) and C₂H₂/(C₂H₂+C₂H₄+CH₄) (50%) as detected in one of transformer oil samples results using DGA. The fuzzy logic output is 5.04 which is corresponding to F5 (normal condition).

Centre-of-gravity which is widely used in fuzzy models, was used for defuzzification method where the desired output $z₀$ is calculated as [14]:

$$z₀ = \frac{\int z \mu_c(z)dz}{\int \mu_c(z)dz}$$

(1)

where $\mu_c(z)$ is the membership function of the output.
D. IEC Ratio Method:
The developed set of fuzzy rules relates the input and the output variables is shown in Fig. 6. The model is tested with inputs, \( \text{C}_2\text{H}_2/\text{C}_2\text{H}_4 \) (2.5), \( \text{CH}_4/\text{H}_2 \) (2.5) and \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_6 \) (2.5) as detected in one of transformer oil sample s results using DGA. The fuzzy logic model output is 7.07, which is corresponding to F3 (partial discharge).

E. Roger’s Ratio Method
The developed set of fuzzy rules relates the input and the output variables for this method is shown in Fig. 7. The model is tested with inputs, \( \text{C}_2\text{H}_2/\text{C}_2\text{H}_4 \) (2.5), \( \text{CH}_4/\text{H}_2 \) (2.5), \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_6 \) (2.5) and \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_6 \) (2.5) as detected in one of transformer oil samples DGA results. The fuzzy logic model results in 11 as shown in Fig. 7. This output is corresponding to F6 in Fig. 2, which is out of code case which reveals that DGA results of this oil sample cannot be diagnosed using Roger’s ratio method.

IV. DGA AND MODEL RESULTS
Several oil samples have been collected from different transformers of various service spans and DGA has been performed on all samples. Table II shows the DGA (in ppm) for 20 oil samples and the corresponding interpretation using traditional techniques and the developed fuzzy logic model for each method. The following observations can be concluded from Table II.
This paper introduces a fuzzy logic model for various DGA interpretation techniques such as Doernenburg, IEC, Rogers ratio and Duval triangle methods. The fuzzy logic models are developed based on 2000 DGA results that have been collected from various in-service and faulty transformers. Results show that all interpretation techniques for DGA results do not necessarily lead to the same conclusion and they may result in inconsistent outcomes for the same oil sample. Results also show the accuracy of the developed fuzzy logic models in DGA interpretation and classification. These models are easy to implement and they do not call for an expert to interpret the DGA results. These models can be used to standardize the interpretation of DGA results.

REFERENCES


