Power Transformer Fault Diagnosis using DGA based on Three Gas Ratio and Fuzzy Logic

Nagesh Kalidas Bhosale, Chandra O. Reddy, Pankaj Bhakre

Abstract: For power system equipment with oil as insulating medium such as power transformer, Dissolved Gas Analysis (DGA) of oil is very helpful method in order to detect faults below oil level. Early detection of fault conditions in a transformer is possible if analysis of gases is done which gets evolved in it. Analysis of the specific value of every gas helps in diagnosing faults. Faults which can be identified by this method include disturbances like presence of corona discharge, partial discharges, arcing and increase in temperature. If correct preventive actions are initiated early for the diagnosis of gases produced, failure to equipment will get prevented. Even though many methods are researched for fault identification and analysis in power transformers, DGA is much superior in comparison with other techniques as it gives more helpful data about the condition of the transformers in running condition. Different techniques, like key gases and their ratio, and their analyzing them graphically are mainly used to understand DGA samples. For a transformer having multiple faults, above methods fail to diagnose. IEC standards are in use for DGA from many years and valuable experience gained over these years around the world is in use to diagnose internal faults on transformers. IEC three gas ratio technique suggested by IEC is mainly preferred, but in some conditions it can’t correctly identify conditions like no suitable codes for diagnosis and multiple faults. The limitations of the traditional three gas ratio method are: with gas ratio is on the verge of crossing the coding boundary, there is a sharp change in the codes, but actually fuzzied boundary should be used. In this paper, codes "zero", "one", "two" are represented by fuzzy membership functions, then "AND" and "OR" conditions of three gas ratio method are coded into fuzzy logic based statements. MATLAB based scripts prove that the presented technique surely overcome the limitations of the traditional three gas ratio method, hence, it largely reduces the errors in diagnosis. In this paper, a method on the basis of fuzzy logic is explained which is able to identify many faults in oil insulated equipment. The presented diagnosis technique uses values of the ratios CH4/H2, C2H4/C2H6 and CH4/H2 and the concentration of specific gases namely methane (CH4), hydrogen (H2), acetylene (C2H2), carbon monoxide (CO), ethylene (C2H4), carbon dioxide (CO2) and ethane (C2H6). Values of these three ratios reflect various patterns of faults inside the transformer. Fuzzy three ratio technique can also quantitatively indicate the likelihood of identified fault with more accuracy as compared to conventional three ratio method.

This tool will prove to be very useful to the engineers in DGA result interpretation.

Index Terms: Dissolved Gas Analysis (DGA), Fuzzy Logic, Power Transformer, Three Gas Ratio.

I. INTRODUCTION

Electrical power sector is the backbone of every country for economic and industrial growth. Growth of any country is dependent on its facility to generate, transmit and utilize the electrical power. Presently with the advances in science and technology for analysis purpose, various new tolls are available and it is possible to locate early the cause of disturbance or fault in the power system and its components. Transmission and distribution of an electrical power has very important role of power transformers. Complete loss of transformer can lead to loss of electrical power and reliability over a longer duration and need costly repairs. Early location of faults in power equipment can achieve major economic and safety objectives in electrical power systems. Different oil cooled and insulated components are used in power sector and their protection and operational safety are major concerns. In the current economic climate, an increased awareness is placed on the reliability of the existing electric power supply. Often, the overloading increases the stress on the transformer. The resultant thermal, electrical and mechanical stress must be conditioned and monitored from reliability and safety point of view. Scheduled monitoring and testing of oil in a transformer is a part of preventative maintenance program. With a preventive approach, the efficiency and life of the transformer can be improved. An internal fault in transformer must be detected early, to prevent further damage and ageing of the transformer. Transformer oil is a composition of hydrocarbons and faults can are not be prevented inevitable if appropriate care is avoided. Transformer oil degrades because of different reasons like ageing, increase in voltage, surrounding conditions, overheating and various other factors. During oil degradation, a number of hydrocarbons such as acetylene, methane, ethylene, ethane and others are generated. Also a number of gases like hydrogen, carbon dioxide and carbon monoxide are produced. These evolved gases under enclosed condition can lead to an explosion. Generation and concentration of these gases is dependent on the oil condition and therefore, it is very important to monitor presence and value of these harmful gases in the transformer under running condition.

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Contamination and ageing of transformer oil and various insulating materials can be monitored by various methods like Factor of dissipation, Voltage to Breakdown of oil and other dielectric materials, capacitance, loss angle, Polymerization Degree etc. DGA is most generally used technique to identify the internal faults in oil insulated transformers and electrical components. Several diagnosis methods, like Key Gas, Rogers Ratio, Dorenbürg’s Ratio, International Electric Committee (IEC) and Duval’s Triangle methods are available to identify the various type faults generally occurring in running condition like corona loss, sparking, partial discharges and temperature rise etc. The DGA results inform about the transformer condition and warning about faults occurring, monitoring the fault development rate, confirmation of the presence of faults, scheduling repairs and condition monitoring during overload. In conventional method, the interpretation of fault diagnosis results in power transformer depends on the human expertise. Sometimes a large inconsistency and inaccuracy is observed regarding conclusion of result by different human experts. So Artificial Intelligence (AI) techniques used for DGA like Artificial Neural Network (AAN), Fuzzy Interface System (FIS), Genetic Algorithm (GA), Self Organizing Map (SOM) and Discrete Wavelet Network (WNs) etc. increases the diagnosis accuracy. This paper proposes an efficient method to correctly diagnose different faults on a transformer with the help of fuzzy logic in coordination with the conventional IEC three gas ratio method.

II. TRADITIONAL THREE GAS RATIO APPROACH

Transformer during fault produces gases due to insulating oil degradation or by some other insulating/dielectric material, for example paper or cellulose material. When partial or full discharge or excess heating takes place, oil in circulation near fault decomposes in some gases. These gases dissolve in oil. Different fault types are therefore reflected by the different compositions of the gases-in-oil.

In this method the concentration and gassing rates of the key hydrocarbon gases is monitored. The key gases analyzed are, hydrogen (H₂), methane (CH₄), ethane (C₂H₆), ethylene (C₂H₄), acetylene (C₂H₂), carbon monoxide (CO), and carbon dioxide (CO₂). The concentrations are expressed in ppm. Normal concentration during operation of these gases with reference to IEC 60599 is as shown in Table I.

| Gas   | Concentration (ppm) |
|-------|---------------------|
| H₂    | 60-150              |
| CH₄   | 40-110              |
| C₂H₆  | 50-90               |
| C₂H₄  | 60-280              |
| C₂H₂  | 3-50                |
| CO    | 540-900             |
| CO₂   | 5100-13000          |

Table I. Dissolved gas compositions [3]

Defined ranges of the ratio & Codes of different ratios of gases

|        | C₂H₂/ C₄H₆ | CH₄/ H₂ | C₂H₂/ C₄H₆ |
|--------|------------|--------|------------|
| < 0.1  | 0          | 1      | 0          |
| 0.1-1  | 1          | 0      | 0          |
| 1-3    | 1          | 2      | 1          |
| > 3    | 2          | 2      | 2          |

Table II. IEC codes [3]

Table III. Fault classification of faults by IEC three gas ratio codes [3]

| SN | Fault type                        | C₂H₂/ C₄H₆ | CH₄/ H₂ | C₂H₂/ C₄H₆ |
|----|----------------------------------|------------|--------|------------|
| 1  | No fault                         | 0          | 0      | 0          |
| 2  | Partial discharges of low energy density | 0          | 1      | 0          |
| 3  | Partial discharges of high energy density | 1         | 1      | 0          |
| 4  | Discharges of low energy density | 1 or 2    | 0      | 1 or 2    |
| 5  | Discharges of high energy density | 1          | 0      | 2          |
| 6  | Thermal fault of low temperature <150°C | 0          | 0      | 1          |
| 7  | Thermal fault of low temperature 150-300°C | 0          | 2      | 0          |
| 8  | Thermal fault of medium temperature 300°-700°C | 0          | 2      | 1          |
| 9  | Thermal fault of high temperature >700°C | 0          | 2      | 2          |

IEC standards are in use for DGA from many years and valuable experience gained over these years around the world is in use to diagnose internal faults on transformers. Initial conclusions were focused on certain gas components like H₂ and CH₄ for findings about oil discharges. “Guide for Interpretation of the Analysis of Gases in Transformer and Other Oil Filled Electrical Equipment in Service” is the guide for standard techniques of DGA provided in year 1978 by IEC. Respective gases under consideration to calculate shown ratio of gases and their referred limits is as shown in Table II. Codes like 0, 1 and 2 are given with respect to ratio value calculated for two gases each and respective fault is characterized as given in Table III.

* Diagnosing steps for Conventional Three Ratio Method

Step1: Get DGA sample report for sampled oil of transformer, take a note of concentration values for various gases such as like hydrogen (H₂), methane (CH₄), ethane (C₂H₆), ethylene (C₂H₄), acetylene (C₂H₂), carbon monoxide (CO), and carbon dioxide (CO₂) in parts per million.

Step 2: Calculate given three ratios of gases \( r_1 = \text{Acetylene (C₂H₂)} / \text{Ethylene (C₂H₄)} \), \( r_2 = \text{Methane (CH₄)} / \text{Hydrogen (H₂)} \), and \( r_3 = \text{Ethylene (C₂H₄)} / \text{Ethane (C₂H₆)} \).

Step 3: With reference to Table II, every ratio is identified with a classified code 0, 1, or 2.
Step 4: For traditional logic used in diagnosis by IEC rules, statements with the use of “AND” and “OR” logic are formed to make decision by referring Table III, and then respective type of fault amongst these nine faults given in Table III is obtained.

Step 5: In case of any no-decision condition, the term ‘Not diagnosable (No Result)’ is used.

Step 6: A result window shows gas content (ppm), corresponding IEC code and decision regarding fault by conventional IEC three gas ratio method.

- **Limitations of the traditional three gas ratio method**
  IEC 599 calculates three ratios of gases, $C_2H_2 / C_2H_6$, $CH_4 / H_2$ and $C_2H_4 / C_2H_6$, where each ratio is provided with a classified code of zero, one or two. In all there are total twenty-seven possible combinations or types of fault, whereas IEC 599 defined only possible eleven conditions whereas remaining sixteen combinations lead to no decision diagnosis.

The codes used consider only two conditions of whether “True” or “False” for identification of fault. This is always not working, because boundaries between separating these codes need to be non-linear or fuzzy. This can be done with the help of much more accurate methods of analysis like fuzzy logic based diagnostic method given and implemented as given below [3].

### III. FUZZY LOGIC BASED THREE GAS RATIO METHOD

Through the use of fuzzy logic with IEC three gas ratio method; the paper presents fuzzy three gas ratio method. To overcome disadvantage of sharp change at boundary condition, this fuzzifies the coding boundary.

- **The fuzzification of the three-ratios**
  As shown in Table II, $r_1$, $r_2$, and $r_3$ are the ratios of gases observed during DGA and are coded with zero, one, and two to represent various ratio ranges.

  With reference to Table III, certain codes for three ratios of gases represent specific type of fault. For example, with the diagnosis of transformer with fault number eight, where $r_1$, $r_2$, and $r_3$ are 0, 2 and 1 respectively. For conventional IEC based analysis, the logical ‘AND’ and ‘OR’ operations are applied. For instance: $r_1 = 0$ AND $r_2 = 2$ AND $r_3 = 1$, from the traditional logic condition, it is either one (true) or zero (false). The method has the disadvantage of the traditional IEC method that with the ratio of gas changing across coded boundary, code changes suddenly between 0, 1, and 2.

  In fuzzy logic based method, codes used in IEC (0, 1 and 2) are replaced with fuzzy codes ZERO, ONE, TWO for each ratio of gas and represented with fuzzy vector $\mu$-function as shown below:

  - $\mu_{\text{ZERO}}(r_1)$, $\mu_{\text{ONE}}(r_1)$, $\mu_{\text{TWO}}(r_1)$ represent the membership function for fuzzy set ZERO, ONE and TWO.

  In the following part, $r_1$ is taken as an example to explain how to transfer IEC codes 0, 1 and 2 into fuzzy set ZERO, ONE, and TWO.

Similarly, representation of fuzzification method for code 0, 1 and 2 with ratio $r_2$ and $r_3$ can be shown.

- **Steps for fuzzy three gas ratio method**
  Step1: Get DGA sample report for sampled oil of transformer, take a note of concentration values for various gases such as like hydrogen ($H_2$), methane ($CH_4$), ethane ($C_2H_6$), ethylene ($C_2H_4$), acetylene ($C_2H_2$), carbon monoxide (CO), and carbon dioxide ($CO_2$) in parts per million.

  Step 2: Calculate given three ratios as $r_1 = \text{Acetylene (C}_2\text{H}_2) / \text{Ethylene (C}_2\text{H}_4)$, $r_2 = \text{Methane (CH}_4) / \text{Hydrogen (H}_2)$, and $r_3 = \text{Ethylene (C}_2\text{H}_4) / \text{Ethane (C}_2\text{H}_6)$.

  Step 3: Every gas ratio is represented by fuzzy based membership functions.

  Step 4: In conventional logic “AND” and “OR” statements are in use for the traditional IEC based diagnosis method, replacing “AND” with “minimum”, “OR” with “maximum”, the diagnosis vector based on fuzzy logic Fuzzy, with $i = 1, 2, \ldots, 9$ representing $i^{\text{th}}$ fault as given in Table III is identified by the below equations [3]:

  $$F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$

  $F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$

  $$F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{max}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$

  $$F_{\text{min}}(r_1) = \text{minimum} \left( \mu_{\text{ZERO}}(r_1), \mu_{\text{ONE}}(r_1), \mu_{\text{TWO}}(r_1) \right)$$
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Fuzzy7 = minimum [ \( \mu_{\text{ZERO}}(r_1), \mu_{\text{TWO}}(r_2), \mu_{\text{ZERO}}(r_3) \) ]
Fuzzy8 = minimum [ \( \mu_{\text{ZERO}}(r_1), \mu_{\text{TWO}}(r_2), \mu_{\text{ONE}}(r_3) \) ]
Fuzzy9 = minimum [ \( \mu_{\text{ZERO}}(r_1), \mu_{\text{TWO}}(r_2), \mu_{\text{TWO}}(r_3) \) ]

Step 5: Type of fault among the nine listed fault types is identified.
Step 6: Result is displayed in graphical type windows with content of gases in ppm, and fuzzy logic based three gas ratio method’s diagnosis [3].

IV. RESULTS AND DISCUSSION

To validate the performance of fuzzy logic based three gas ratio method presented in the paper, DGA result of 18 oil samples with type of fault occurring is already known [3]. MATLAB scripts are programmed according to the steps mentioned in chapter V and results are analyzed below.

Fuzzy Inference System (FIS) is a tool of presenting the diagram from provided inputs to an output based on fuzzy logic. The method involves all of the portions related to membership functions, logical operators and if-then statements. Here a Mamdani FIS is used as shown in fig. 4, with three inputs, one output and eleven rules, with the aid of MATLAB’s Fuzzy Logic Toolbox R2017a. A Rule viewer with eleven rules is shown in fig. 5.

Fig. 4. FIS editor for fuzzy three ratio method

Fig. 5. Rule viewer for fuzzy three ratio method

Fig. 6. Fuzzification method for code 0 with ratio \( r_1 \)

Fig. 7. Fuzzification method for code 1 with ratio \( r_1 \)

Fig. 8. Fuzzification method for code 2 with ratio \( r_1 \)

Fig. 9. Fuzzification method for code 0 with ratio \( r_2 \)

Fig. 10. Fuzzification method for code 1 with ratio \( r_2 \)

Fig. 11. Fuzzification method for code 2 with ratio \( r_2 \)
V. CONCLUSION

The traditional IEC based three gas ratio method is applied for various oil samples in the paper with the help MATLAB based software programming, and is tested to diagnose different types of faults commonly occurring in the transformer. Fuzzy Logic based three gas ratio method is more informative towards the transformer incipient faults providing reliable information to the maintenance engineer and at the same time maintaining integrity of the original method.
Fuzzy membership functions represent more accurate relation between the type of fault and DGA samples as reflected in the output results. Also with the method, more than one fault at a time can be identified, which is not correctly diagnosed by the traditional method. The paper also presents diagnosis of faults in a transformer using fuzzy logic based three gas ratio. This concept can remove the limitations of traditional IEC based three gas ratio method like: no diagnosis and not able to diagnose many faults occurring at a time. Also the method is not required to waste time in “learning” and its coding is simplified with modern day software applications. Programming results with DGA analysis of oil samples for a power transformer, shows that the method is working properly and error percentage of the presented method is much less than that of the traditional IEC based method.

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