COMPARATIVE STUDY OF VARIOUS DISSOLVED GAS ANALYSIS TECHNIQUES AND EFFECTIVENESS OF USING FUZZY LOGIC INTERPRETATION APPROACH

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Abstract:

Assessment techniques for judging power transformer conditions and lifespan has been eye-catching. Dissolved Gas Analysis (DGA) has proved to be useful tool for diagnostic of incipient and potential faults in power transformers. This paper discusses pros and cons of the various DGA methods in practice and also deals with an experimental investigation carried out to study relation between gas generation and partial discharge. In the second part, a fuzzy logic based interpretation method (FLI), which is based on fuzzy set theory is described and implemented as an improved DGA interpretation method that provides higher reliability and precision of the fault diagnostics.

Keywords: Transformer Oil, Partial Discharge (PD), Dissolved Gas Analysis (DGA), Fuzzy Logic Interpretation (FLI).

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I INTRODUCTION

For the transformers in service, it has become imperative to timely assess the operating conditions of such expensive equipments to avert any snag in their operating condition. Consequently inspections have gained significant importance in order to ensure diagnostic of incipient faults and implementation of necessary maintenance plans to enhance their lifespan.

In the case of open-breather transformers, insulating oil is highly prone to undergo changes in its chemical and dielectric properties due to oxidation reactions. The main agents of oxidation are temperature, moisture and oxygen. Reaction accelerators are copper,

aluminium and electrical and thermal stresses . Since the transformer oil represents an important information carrier to determine which the operating condition is of the power transformer.

$CxHy + O2 \rightarrow$ Acids, H2O, Sludge and Gas by-products

The hydrocarbon nature of mineral transformer oil, oxidation occurs via breakdown of hydrocarbon compounds into small and highly reactive molecules known as free radicals. These lead to quick chain reactions that combine oxygen to form peroxide radicals in a chain of reactions. Faults may occur due to electrical and thermal stresses. These faults can be differentiated for their energy, localization and occurrence period. Along with a fault, there are increased oil temperatures and generation of certain oxidation products such as acids and soluble gases. The electrically induced ageing process due to partial discharge (PD) phenomena. A PD is a highly localized discharge that may be precursor to a breakdown discharge within the insulation system. The gaseous ageing products dissolved in transformer oil are: hydrogen, methane, ethane, ethylene, acetylene, propane, propene, together with carbon monoxide and carbon dioxide, nitrogen and oxygen. These gases are considered as fault indicators and can be generated in certain patterns and amounts depending on the characteristics of the fault. Low energy faults leads to formation of hydrogen and saturated hydrocarbon C1 to C2, and high energy faults tend to generate unsaturated hydrocarbons C2+n containing double or triple bonds. Hence, qualitative and quantitative determination of dissolved gases in transformer oil may be of great importance in order to assess fault condition and further operating reliability of power transformers.

II Analysis of Fault Gas and Intricacies involved:

Through application of DGA technique, fault gases dissolved in oil can be determined and interpreted. State of the art online monitoring systems by DGA have become highly advantageous and suitable to detect any abnormal increase of gas concentrations due to any incipient or potential fault developing in a power transformer. Several DGA interpretation schemes have been proposed and applied for fault diagnostics. Generally, these interpretation schemes are based on empirical assumptions and practical knowledge gathered by experts all over the world.

In some cases, DGA interpretation schemes may differ with respect to type and amount of identified faults. That fact is for sure in conflict towards a reliable fault diagnostics.Most of the interpretation schemes are generally based on defined principles such as, gas concentrations, key gases, key gas ratios, and graphical representations. Some of the more applied interpretation schemes are IEC 60599, Key Gas Analysis, Roger and Doernenberg Ratio Methods, Duval Method and Gas Nomograph Method. They are included into the IEEE Standard C57.104-1991

III OVERVIEW OF CURRENT DGA INVESTIGATION METHODS IN PRACTICE:

3.1 Key Gas Method :

The presence of the fault gases depends on the temperature or energy that disrupts the chemical structure of the insulating oil. This method detects faults by measuring individual gases rather than by calculating gas ratios. The significant and proportion of the gases are called “key gases”. The tables 1 and 2 describes the type of faults depending upon the various gas compositions.

To Calculate the total of dissolved combustible gases (TDCG):

TDCG = H_2 + CO + CH_4+ C_2H_6 + C_2H_4 +C_2H_2.

1) TDCG < 720 PPM : Operating satisfactorily

2) TDCG = 721 to 1920 PPM: Faults may be present

3) TDCG = 1921 to 4630 PPM: Faults are probably present

4) TDCG > 4630 PPM: Continued operations could result in failure.

KEY GAS	NATURE OF FAULT
Acetylene, C_2H_2	Electrical arc in oil

Hydrogen H_2	Corona , partial discharge
Ethylene C_2H_4	Thermal degradation of oil
Carbon Monoxide	Thermal ageing of oil

Table:1 Various Types of Faults Depending on the Gas Composition

Gas Content		Nature of Fault
Major	**Minor**	
Ethylene	Ethane	Thermal Decomposition
Methane	Hydrogen	(Hot Spots)
Hydrogen Methane	Acetylene Ethylene Ethane	Electrical Discharge (Except Corona)
Hydrogen	Methane Ethane	Internal Corona
Carbon Monoxide	---	Cellulosic insulation decomposition
Carbon Dioxide		

Table:2 Various Types of Faults Depending on the Mixed Gas Composition

3.2 Dorrnenburg Ratio Method

For convenient fault diagnosis, gas ratio methods use coding schemes that assign certain combinations of codes to specific fault types.The codes are generated by calculating ratios of gas concentrations and comparing the ratios with predefined values derived by experience and continually modified. A fault condition is detected when a gas combination fits the code for a particular fault.The Dorrnenburg Ratio method identifies faults by analyzing gas concentration ratios such as CH_4/H_2, C_2H_2/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4, which can be used to identify thermal faults, corona discharge and arcing. This method, which is specified in IEEE Standard C57.104-2008, characterizes dissolved gases of transformer oil. However, the method may obtain numerous “no interpretation,” results due to incomplete ratio ranges.

3.3 Roger’s Ratio Method

The most common gas ratio method is the Rogers ratio method, which distinguishes more thermal fault types compared to the Dorrnenburg ratio method. The Rogers method analyzes four gas ratios: CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. Faults are diagnosed via a simple coding scheme based on ranges of the ratios. This method is effective because it correlates the results of numerous failure investigations with the gas analysis of each case. However, some ratio values are inconsistent with the diagnostic codes assigned to various faults in this method. Also, since the method does not consider dissolved gases below normal concentration values, a precise implementation of the method may still misinterpret data.

3.4 Nomograph Method

This improves the accuracy of fault diagnosis by combining fault gas ratios and the concept of Key Gas threshold. By graphically presenting fault gas data, it simplifies interpretation of fault gas data. A nomograph is a series of vertical logarithmic scales for representing the concentration of individual gases as straight lines drawn between adjacent scales. The lines connect points representing the values of individual gas concentrations. Straight lines are diagnostic criteria for determining fault type.Fault types are identified by visually comparing the slopes of line segments with the keys at the bottom of the nomograph. Fault severity is indicated by the position of lines related to the concentration scales.The threshold value of each vertical scale is indicated by an arrow. For the slope of a line to be considered significant, at least one of the two tie points should exceed the threshold value. The fault is not considered significant if the tie point lies above a threshold value.

3.5 IEC Ratio Method

The IEC Ratio Method excludes the C_2H_6/CH_4 ratio, which only indicates a limited temperature range of decomposition. Here, the remaining three gas ratios have different ranges of code in comparison with the Rogers ratio method. The four detected conditions are normal ageing, partial discharge of low and high energy density, thermal faults and electrical faults of varying severity.

However, it does not classify thermal and electrical faults into precise subtypes. Dissolved gases must be assessed for 'normality' limits before interpretation by ratios. Another improvement in the second version of IEC method is the 3D graphical representation of ratio ranges. Faults that cannot be diagnosed are plotted onto the graph so that its nearest distance to a certain fault region can then be observed. Power transformer faults are typically classified as partial discharges, discharges of low and high energy, and thermal faults in which severity depends on fault temperature.

3.6 Duval Triangle Method

The Duval Triangle Method uses values of only three gases Metane CH_4, Ethene C_2H_4 and Ethyne C_2H_2 and their location in a triangular map. The three detectable faults are partial discharges, electrical faults (high and low energy arcing), and thermal faults (hot spots of various temperature ranges). Although this method is easily performed, careless implementation can obtain false diagnoses since no region of the triangle is designated as an example of normal ageing. Hence, before using this method to analyze transformers that have been in service for the many years, the permissible amount of dissolved gases should be determined. An identified problem is diagnosed by calculating the total quantities of the three Duval Triangle gases (CH_4, C_2H_4 and C_2H_2) and dividing the quantity of each gas by the total to find the percentage of each gas of the total. The percentages of the total are then plotted on the triangle to obtain the diagnosis.

3.7 CIGRE Method:

CIGRE proposed a DGA interpretation method that has attempted to improve previous interpretation schemes with the purpose to contribute to more reliable fault diagnostics. The

CIGRE Interpretation (CI) scheme consists of a two-step evaluation based on key ratios of gas concentrations and key gas concentrations, both of them compared to thresholds.FIS (Fuzzy Interface System) adopted here to improve the CIGRE interpretation (CI). The use of a FIS as a tool could already eliminate some deficiencies of CI on the basis of the following statements. CI describes two methods that use two key criteria for fault detection. The new approach uses two key criteria as well, but they have been well integrated into one single method.CI uses thresholds to decide whether a transformer is faulty or not. That can lead to wrong interpretation, especially in case of values close to the thresholds. This new approach eliminates thresholds and uses steady membership functions instead.CI attempt to define the type of fault that might be taking place. The new approach estimates the likelihood of fault occurrence for each possible fault types. However, DGA may not reliably predict rapidly occurring instantaneous faults. Instantaneous failures that cannot be prevented by DGA are: (1) flashover with power follow-through, and (2) serious failures that develop too rapidly for detection by DGA.

IV BASICS OF FUZZY-INFERENCE-SYSTEM (FIS)

Fuzzy sets differ to binary sets in the number of feasible membership values. While for binary sets two membership values, {0, 1}, are defined, fuzzy sets additionally use pseudo-membership values, [0,1] .For the class of fuzzy logic that has been proposed by Mamdani or Sugeno, production rules map fuzzy sets to other fuzzy sets. Production rules are a pre-condition for qualitative modeling by FIS. Qualitative modelling with FIS (Fig. 1) is based on three main steps of mapping.

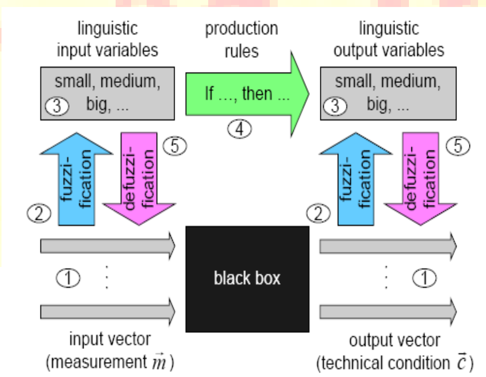

Fig. 1: Transformation by means of a FIS subdivided in main steps

The first step is known as fuzzification (Fig. 1-2).In this step a physical problem is transformed into a linguistic problem. For this purpose both the input vector and the output vector (Fig. 1) are mapped to linguistic variables (input variables and output variables, respectively, (Fig. 1-3) by means of membership functions of type $\mu:\Re \rightarrow [0,1]$ .Within the second step, called inference, production rules (Fig. 1-4) adjust the mapping of the output vector to the linguistic output variables based on the mapping of the input vector to the linguistic input variables. Each rule can conjunctively or disjunctively combine two or more premises (membership value of an input value to a linguistic input variable). Furthermore, production rules can be weighted depending on how reliable they are. Thus, the linguistic problem can be solved. The last step is to perform defuzzification (Fig. 1-5). That means the already solved linguistic problem will be converted into a physical problem that is also solved. Mamdani and Sugeno type fuzzy logic differ fundamentally in steps ‘inference’ and ‘defuzzification’.

V. NEW FUZZY LOGIC INTERPRETATION (FLI) BASED ON FIS

One deficiency of CI that has already been mentioned ahead is the usage of two independent interpretation methods for fault detection. One of these methods depends on key gases, the other on key gas ratios. By contrast, fuzzy logic interpretation (FLI) can incorporate both of those methods in a single method that can consider both criteria (key gas concentrations and key gas ratios) simultaneously for each fault type. Only, the fault ‘tank tap changer’ depends on single criteria. The major outcome of this integration is an improved interpretation and therefore a more reliable fault diagnosis.

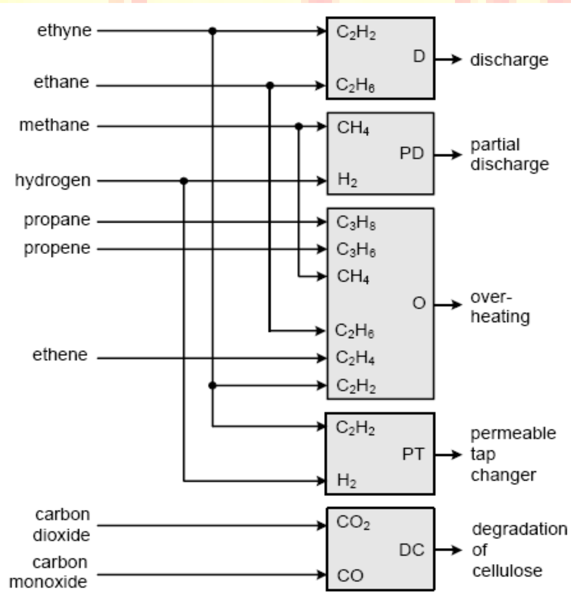

Fig:2 Considered measurements per type of fault

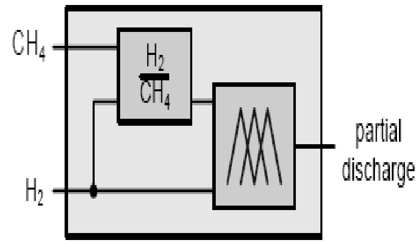

Fig. 3: Relevant key gases and key gas ratios to detect partial discharge

FUZZIFICATION

FIS integrates two 1-dimensional domains from CI, namely key gas hydrogen (H) and key gas ratio hydrogen/methane (HM), in one single 2-dimensional domain as represented in Fig. 4 given below

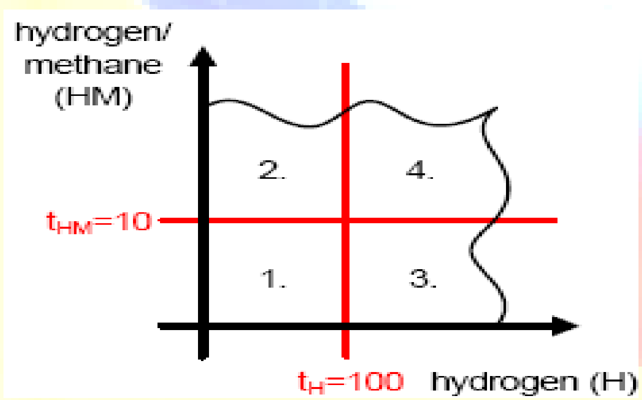

Fig:4 Combination of two 1-dimensional domains to a 2-dimensional domain.

For each threshold, tx , with x ∈{HM,H}, FIS places a pair of sigmoid membership functions in accordance to equation (1) and (2). Parameter b in these equations is set to tx , thus constraint μb (a,b;x = tx)=μs (a,b;x=tx)= 0.5 is fulfilled.

$$\mu_b(a,b;x) = \frac{1}{1+e^{-a(x-b)}}, a \in \Re \qquad (1)$$

$$\mu_s(a,b;x) = 1 - \mu_b(a,b;x) \qquad (2)$$

Sigmoid membership functions are steady. This property is an inevitable pre-condition for a FIS. For the image set 'partial discharge' (PD) FIS uses singleton membership functions accordant to equation (3). For each i ∈{vu,u,l,vl} a membership function μi (c;PD) maps a likelihood value c for PD to a corresponding singleton.Singletons are typical for zero-order Sugeno type fuzzy inference. They make defuzzification much easier and faster than in Mamdani type fuzzy inference.

$$\mu_i(c;PD) = \begin{cases} 1, \text{ if } \text{PD} = c \\ 0, \text{ else} \end{cases} \qquad (3)$$

The Table:3 shows for each value linguistic variables and corresponding membership functions with their parameterization. The settings '0' and '100' for parameter c are a direct outcome of CI, but settings '33' and '66' are estimations. Estimations were done based on the significance of the production rule.

Value	**Linguistic Variable**	**Membership function**	**Parameterization**
H	Small	μs (a,b;H)	(a,b)= (0.08,100)
	Big	μb (a,b;H)	
HM	Small	μs (a,b;HM)	(a,b)= (0.08,10)
	Big	μb (a,b;HM)	
PD	Very Unlikely	μvu (C ;PD)	C = 0
	Unlikely	μu (C ;PD)	C = 33
	Likely	μl (C ;PD)	C = 66
	Very Likely	μvl (C ;PD)	C = 100

Table:3 Membership functions and parameterization to detect partial discharge.

VI. COMPARISON BETWEEN CI AND FLI

The in-house software TRAFADETO – Transformer Fault Detection Tool, has been developed to implement the new fuzzy logic interpretation method (FLI). This software was applied to compare CI and FLI by means of the results obtained from above mentioned experimental measurements. For application of this software maximum gas concentrations obtained from conduction of experiments of gas generation by PD-stressing (Fig. 3 and 5) were used as a measurement vector, see Tab. 5.

Production rule	Weight
If H is big and HM is big, then PD is very likely	1/4
If H is big and HM is small, then PD is unlikely	1/4
If H is small and HM is big, then PD is likely	1/4
If H is small and HM is small, then PD is very unlikely	1/4

Table 4 : Production rules that are used to detect PD

		PD#1	PD#2
Gases (ppm)	CO	3.7	14
	CO_2	410	434
	H_2	152	847
	CH_4	9.1	135
	C_2H_6	2.3	43.9
	C_2H_4	1.8	105
	C_2H_2	3.3	202
	C_3H_8	0.7	11
	C_3H_6	1.6	33

Table:5 Measurement vectors with maximum hydrogen

Interpretation of DGA by CI resulted in the diagnostics of following faults: discharge (D), partial discharge (PD), overheating (O), permeable tank tap changer (PT) and degradation of cellulose (DC). As one can see in Tab. 6, key gas and key gas ratio method from CI resulted in uncertain diagnostic of faults. For instance, in case of for PD #2, the key gas method identifies D and PD as faults, whereas key gas ratio method identifies D, O and DC as faults.

Key gas method		**Estimated Faults**	**Key gas method**	
PD#1	**PD#2**		**PD#1**	**PD#2**
No	Yes	**D**	No	Yes
Yes	Yes	**PD**	Yes	No
------	-----	**O**	No	Yes
No	No	**PT**	No	No
No	No	**DC**	Yes	Yes

Table 6: Measurement vectors with maximum hydro Estimated faults by key gas method and key gas ratio method of CI.

By contrast, Table:7 shows the results of interpretation of DGA by FLI. In case of PD #1 the FLI estimated PD as the most likely fault. Nevertheless, 60% likelihood of DC suggests that the pressboard plate in between the bare-plate electrode system could have been affected. In Case of PD #2 the FLI estimates D and O as most likely faults. That might be due occurrence of a strong PD and discharge. Furthermore, PD #1 suggested a likelihood of 60 % DC that may indicate effect of pressboard. The likelihood of 36.2% PD indicates the strong PD stressing prior to the discharge. The likelihood of 99.9% for overheating was inconsistent and therefore suggests that this model should be further improved. Future work will focus on that point.

		PD#1	PD#2
Estimated likelihood of fault (%)	D	58.3	100.0
	PD	99.2	36.2
	O	9.0	99.9
	PT	0.0	1.0
	DC	60.0	60.0

Table:7 Estimation of fault likelihood by FLI.

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VII. Conclusion:

On perusal of the various DGA Techniques it transpires that almost all the existing methods have its own draw backs and prone to cater erroneous result which may lead us to the deception. Out of all methods in practice the CI method is quite reliable compared to all other methods. The deficiency of CI that has already been mentioned ahead is the usage of two independent interpretation methods for fault detection. One of these methods depends on key gases, the other on key gas ratios. By contrast, fuzzy logic interpretation (FLI) can incorporate both of those methods in a single method that can consider both criteria (key gas concentrations and key gas ratios) simultaneously for each fault type. The major outcome of this integration is an improved interpretation and therefore a more reliable fault diagnosis.

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