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Application of Fuzzy Logic in Fault Diagnosis in Transformers using Dissolved Gas based on Different Standards

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***Abstract*—**One of the problems in fault diagnosis of transformer based on dissolved gas, is lack of matching the result of fault diagnosis of different standards with the real world. In this paper, the result of the different standards is analyzed using fuzzy and the result is compared with the empirical test. The comparison between the suggested method and existing methods indicate the capability of the suggested method in on-line fault diagnosis of the transformers. In addition, in some cases the existing standards are not able to diagnose the fault. In theses cases, the presented method has the potential of diagnosing the fault. The information of three transformers is used to the show the capability of the suggested method in diagnosing the fault. The results validate the capability of the presented method in fault diagnosis of the transformer.

***Keywords*—**Fault Diagnosis of Transformer, Dissolved Gas, Fuzzy Logic.

I. Introduction

VOLTGAE breakdown in liquid insulator of transformer releases gas in the transformer. The gas distribution can show the kind of fault and the gas ratio indicates the severity of the fault in the transformer. There are several methods in fault diagnosis based on the dissolved gas of the transformer [1-11] such as Test of Combustible Gas (TCG). In TCG the combustible gas is collected from the transformer. This method does not give the amount of each component in the produced gas.

The conventional method in fault diagnosing is analysis of dissolved gas in the transformer oil. The main advantage of this method is fault diagnosis incipiently. Therefore, the fault can be detected rapidly. The main issue in this method is to obtain the data. The fault can be diagnosed from this data accurately. In this regard, some researchers use extended Rogers method based on Central Electric Generating Board (CEGB). In the standard of International Electric Committee (IEC), based on the Rogers method, a three digit code for three gas ratios, as well as a specific table describes the fault [7].

The standard of American Society for Testing and Material (ASTM) uses a four digit code and a specific table to determine four gas ratios [10].

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It should be noted that if the magnitude of the data is small, the error in the Rogers is high. In addition if different standards are used to detect one fault, the results for the different methods are not the same. As a result, in the studies carried out by the researchers several methods such as expert systems, fuzzy logic and neural network are incorporated in the dissolved gas analysis to obtain more accurate results [1-9].

In the methods that use artificial network the fault diagnosis is based on the operator's information from the approximate amount of gases and the oil appearance of the transformers [1-2]. Since these methods are based on the operator's experience, there is a possibility of the error in the fault diagnosis.

The neural network based methods need precise learning in a broad range of the faults of the transformers in order to get a correct response [3-6]. In the various standards, the fault diagnosis is performed based on the ratios of the produced gases in the oil of transformer. Due to uncertainty of the ratio of the produced gases, the fuzzy logic is used. In this paper, three and four digit codes containing the fault information are created based on the fuzzy logic to achieve better result. The method is applied to three transformers to diagnose the fault by analyzing the dissolved oil based on fuzzy logic.

II. Dissolved Gases in the Transformer Oil

In the normal operation of the transformer, the released gases Hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), acetylene (C_2H_4), ethylene (C_2H_2) and so on. When there is a abnormal situation such as occurring a fault, some specific gases are produced more than in the normal operation and the amount of them in the transformer oil increases. The increase in the amount of gases results in saturation of the transformer oil and no more gas can be dissolved in oil. Therefore, when the oil is saturated, the gas is released from the oil. The amount of the dissolved gas related to the temperature of the oil and the kind of gas. The produced gas can be classified into three groups: polarization, corona and arcing. These groups from the severity of the released energy during the fault are different. The largest and lowest amount of the released energy is associated with the arcing and corona.

1) Polarization

In oil, the released gases at low temperature are CH_4 and, C_2H_6 and at high temperature are C_2H_6, CH_4, C_2H_4 and H_2. In cellulose, the generated gases at low and high temperatures are CO and CO_2.

2) Corona

In corona the produced gas in oil is H_2 and the released gases in cellulose are H_2, CO and CO_2.

3) Arcing

In this case, the released gases are C_2, H_2, C_2H_6, CH_4, C_2H, and H_2.

The produced gas also can be classifieds into three groups:

a) Hydrogen and hydrocarbons: H_2, CH_4, C_2H_4 and C_2H_2.

b) Carbon oxides: CO, CO_2.

c) Non-faulty gases: O_2 and N_2. Methods of Analyzing dissolved gases in oil.

In this method, at first, a sample of the transformer oil is taken. Then, the dissolved gases is extracted, separated and measured by means of chromatography.

In order to interpret the results of experiment, we produce a data in a suitable form to diagnose the fault. The forming this data is based on different standards which explained in the following subsections.

A. IEC Standard

According to IEC, the extended Rogers method is used to produce a three digit code. The code is determined based on three gas ratio C_2H_2/C_2H_4, CH_4/H_2 and, C_2H_4/C_2H_6 as given in Table I.

TABLE I
IEC CODE DETERMINATION CRITERIA

Gas Ratio	Value	Code
$X=C_2H_2/C_2H_4$	X<0.1 0.1<X <3 X>3	0 1 2
$Y=CH_4/H_2$	Y<0.1 0.1<Y<1 Y>1	1 0 2
$Z= C_2H_4/C_2H_6$	Z<1 1<Z< >3 >3	0 1 2

TABLE II
FAULT DIAGNOSIS USING IEC CODES

Code			Kind of Fault	No.
X	Y	Z		
0	0	0	No fault	0
0	1	0	Partial discharge with low energy density	1
1	1	0	Partial discharge with high energy density	2
1 or 2	0	1 or 2	Partial discharge with low energy density	3
1	0	2	Partial discharge with high energy density	4
0	0	1	Thermal fault with temperature less than 150^{0C}	5
0	2	0	Thermal fault with temperature between 150^{0C} to 300^{0C}	6
0	2	1	Thermal fault with temperature between 300^{0C} to 700^{0C}	7
0	2	2	Thermal fault with temperature greater than 700^{0C}	8

B. CEGB Standard

In this standard, a four digit code based on Table III is created using Rogers method and four gas ratios CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6, C_2H_2/C_2H_4.

TABLE III
CEGB CODE DETERMINATION CRITERIA

Gas Ratio	Value	Code
$W=CH_4/H_2$	W<=0.1 0.1< W<1 1<=W <3 W>=3	5 0 1 2
$X=C_2H_6/CH_4$	X<1 X>=1	0 1
$Y=C_2H_4/C_2H_6$	< 1 1<=Y<3 Y>=3	0 1 2
$Z=C_2H_2/C_2H_4$	Z<0.5 0.5<=Z<3 Z>=3	0 1 2

TABLE IV
FAULT DIAGNOSIS USING CEGB CODES

Code				Kind of Fault
W	X	Y	Z	
0	0	0	0	No Fault
5	0	0	0	Partial discharge
1 or 2	0	0	0	Increase in temperature $<=150^{0C}$
1 or 2	1	0	0	Increase in temperature 150^{0C}-200^{0C}
0	1	0	0	Increase in temperature 200^{0C}-300^{0C}
0	0	1	0	Increase in overall temperature in the conductive parts
1	0	1	0	Circulating currents in windings
1	0	2	0	Circulating currents between core and tank
0	0	0	1	Spark with low energy density
0	0	1 or 2	1 or 2	Spark with high energy density
0	0	2	2	Continuous spark
5	0	0	1 or 2	Partial discharge with tracking
CO_2 /CO> 11				Abnormal increase in insulator temperature.

C. ASTM Standard

In this standard a four digit code, is generated based on the codes given in Table V using Rogers method and four gas ratios C_2H_4 /C_2H_6, C_2H_6/CH_4, C_2H_2/C_2H_4, CH_4/H_2. Regarding the obtained codes and data of Table VI, the faults are diagnosed.

TABLE V
THE ASTM CODE DETERMINATION CRITERIA

Gas Ratio	Value	Code
W= CH_4/H_2	$0<W<0.1$ $0.1<W <1$ or W=0 $1<W<3$ $W >3$	1 2 3 4
$X=C_2H_6/CH_4$	$X<1$ $X>1$	0 1
$Y=C_2H_4/C_2H$ 6	$Y<1$ $3< Y < 1$ $Y>3$	0 1 2
$Z=C_2H_2/C_2H_4$	$Z<0.5$ $3 \ < Z< 0.5$ $Z>3$	0 1 2

TABLE VI
FAULT DIAGNOSIS USING ASTM CODES

Code				Kind of Fault
W	X	Y	Z	
2	0	0	0	Normal
1	0	0	0	Partial discharge
3	0	0	0	Increase in temperature $<=150^{0C}$
4	0	0	0	Increase in temperature $<=150^{0C}$
3	1	0	0	Increase in temperature 150^{0C}-200^{0c}
4	1	0	0	Increase in temperature 150^{0C}-200^{0c}
4	1	0	0	Increase in temperature 200^{0C}-300^{0c}
2	0	1	0	Increase in all conductors
3	0	1	0	Circulating currents in windings
3	0	2	0	Circulating currents between core and tank
2	0	0	1	Spark with very low energy density
2	0	1	1	Spark with high energy density
2	0	1	2	Spark with high energy density
2	0	2	1	Spark with high energy density
2	0	2	2	Continuous spark
1	0	0	1	Partial discharge with tracking
1	0	0	2	Partial discharge

In this paper, the ratio of CO2/CO for in each standard is also measured. This value is used in diagnosing of fault location (in oil and cellulose). As explained before, despite the fact that the Rogers method is useful for assessing the transformer insulation, no quantitative criterion is provided for possibility of occurrence of each fault. In the case of occurrence of multiple faults, the gases from different faults are mixed together. As a result, the matching between the gas ratios and code are difficult. This can be overcome by the aid of fuzzy diagnosis as presented in this paper

III. FUZZY LOGIC APPLICATION

In this section the application of the fuzzy logic in fault diagnosis is presented. Regarding the similarities of the three standards, only the procedure of the IEC standard is explained as follows:

Fuzzy IEC Codes

As shown in Table I, in the IEC codes the three gas C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 are labeled by codes of 0,1 and 2, respectively. To make clear the relationship between the range of each gas ratio and its corresponding codes rearranged. Table VII shows the new arrangement of the codes.

TABLE VII
THE REARRANGEMENT OF IEC CODES

Gas Ratio	Code 0	Code 1	Code 2
$X=C_2H_2/C_2H_4$	$X<0.1$	$0.1<X<3$	$X>3$
$Y=CH_4/H_2$	$0.1<Y<1$	$Y<0.1$	$Y>1$
$Z=C_2H_4/C_2H_6$	$Z<1$	$1<Z<3$	$Z>3$

As Table II indicates, the transformer faults are identified based on the three gas ratios $X=C_2H_2/C_2H_4$, $Y=CH_4/H_2$ and $Z=C_2H_4/C_2H_6$. For example if X , Y and Z are value of 0, 2 and 1, respectively, it means fault No. 7, i.e. , thermal fault of medium temperature 300-700^{0}C, is taken place.

In fact, conventional logic "AND" and "OR" are employed. used For example, in the IEC code diagnosis., the 7th fault in Table VII is described by

$$F(7):\ code_{ZERO}(X)\ \text{AND}\ code_{TWO}(Y)\ \text{AND}\ code_{ONE}(Z)$$

In this relation, $code_{ZERO}$(X), $code_{TWO}$(Y) and $code_{ONE}$(Z) represent the coded values of gas ratio X, Y and Z respectively. As a result, fault (F7) will take the value of one(true) or zero(fault).

In the fuzzy method the IEC codes are used to rebuild sets Zero, ONE and TWO Each gas ratio is shown by a fuzzy vector as

$$[\mu_{ZERO}(\bullet), \mu_{ONE}(\bullet), \mu_{TWO}(\bullet)]$$

where $\mu_{ZERO}(\bullet)$, $\mu_{ONE}(\bullet)$ and $\mu_{TWO}(\bullet)$ represent the membership functions for fuzzy codes ZERO, ONE and TWO, respectively,.

The membership function is described by a descending or/and an ascending demi-Cauchy distribution function [2]:

.

$$\mu_d(r) = \begin{cases} 1 & \text{for } r \le A \\ \dfrac{1}{1+\left(\dfrac{A-r}{a}\right)^2} & \text{otherwise} \end{cases} \quad (1)$$

$$\mu_a(r) = \begin{cases} 1 & \text{for } r \ge A \\ \dfrac{1}{1+\left(\dfrac{A-r}{a}\right)^2} & \text{otherwise} \end{cases} \quad (2)$$

where A and a are a pair of parameters which can be chosen to produce appropriate membership function.[2]. The parameters a and A are treated as parameter distribution and boundary parameter, respectively.

The fuzzy IEC codes ZERO, ONE and TWO are produced using Equations (1) and (2). Therefore, fuzzy IEC codes for each set of ratios are determined.

The eight fuzzy diagnosis vectors are formed by substituting the logic operator "AND" with minimization operation and the logic operator "OR" with maximization operation. In fact, the conventional true-false logic is replaced by a fuzzy multi-value logic [12]. Therefore, the following equations are produced based on the IEC rules to diagnose different faults of Table I. Labeled by No. 0 to 8.

$$F(0) = \min[\mu_{ZERO}(X), \mu_{ZERO}(Y), \mu_{ZERO}(Z)]$$

$$F(1) = \min[\mu_{ZERO}(X), \mu_{ONE}(Y), \mu_{ZERO}(Z)]$$

$$F(2) = \min[\mu_{ONE}(X), \mu_{ONE}(Y), \mu_{ZERO}(Z)]$$

$$F(4) = \min[\mu_{ONE}(X), \mu_{ZERO}(Y), \mu_{TWO}(Z)]$$

$$F(5) = \min[\mu_{ZERO}(X), \mu_{ZERO}(Y), \mu_{ONE}(Z)]$$

$$F(6) = \min[\mu_{ZERO}(X), \mu_{TWO}(Y), \mu_{ZERO}(Z)]$$

$$F(7) = \min[\mu_{ZERO}(X), \mu_{TWO}(Y), \mu_{ONE}(Z)]$$

$$F(8) = \min[\mu_{ZERO}(X), \mu_{TWO}(Y), \mu_{TWO}(Z)]$$

$$\begin{aligned} F(3) = \max\{ & \min[\mu_{ONE}(X), \mu_{ZERO}(Y), \mu_{ONE}(Z)], \\ & \min[\mu_{ONE}(X), \mu_{ZERO}(Y), \mu_{TWO}(Z)], \\ & \min[\mu_{TWO}(X), \mu_{ZERO}(Y), \mu_{ONE}(Z)], \\ & \min[\mu_{TWO}(X), \mu_{ZERO}(Y), \mu_{TWO}(Z)] \}. \end{aligned}$$

Normalizing the equations results in

$$F_r(i) = \frac{F(i)}{\sum_{j=0}^{8} F(j)} \quad i = 0-8 \quad (3)$$

Fig. 1 shows compares the conventional IEC code 1 and the fuzzy membership function $\mu_{ONE}(Z)$ for the gas ratio Z=C_2H_4/C_2H_6.

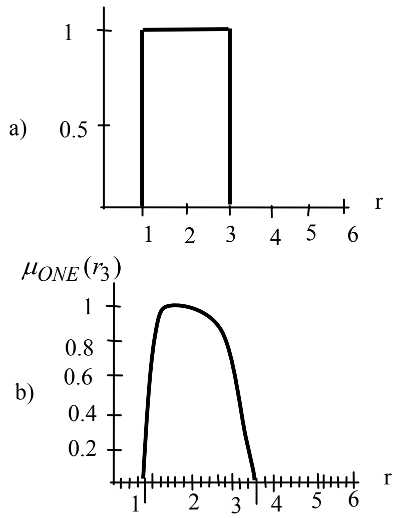

Fig. 1 a) IEC Code 1 b) Fuzzification of IEC code 1 for the gas ratio C_2H_4/C_2H_6 [2]

IV. Results of Simulation

In order to evaluate the performance of the suggested algorithm, three transformers are tested. The amount of the gases of the transformers is given in Table VIII. Transformer 1 belongs to Isfahan Shahid Montazeri power plant. The information of data of Transformers 2 and 3 are given in [7].

TABLE VIII
THE AMOUNT OF GASES IN THE TEST TRANSFORMERS

Transformer Number	**Amount of Gases**				
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6
1	796	999	31	1599	234
2	95	110	<0.1	50	160
3	120	17	4	23	32

The diagnosed faults for the transformers are obtained for two crisp and fuzzy cases using the mentioned standards, and the results are shown in Table IX. In this paper a reliability factor is considered for each transformer in the fuzzy case to obtain better results. As this table shows the fault with larger reliability factor is closer to the actual fault. Also as shown for the crisp case of Transformer 3, when the ratio values of the gases are small, the standards are not able to diagnose the fault. However, suggested method diagnoses the actual fault. Therefore the problem of lack of diagnosing the fault when the values are small, is solved.

V. CONCLUSION

In this paper, the analysis of dissolved gas of the transformer is used to diagnose the faults in the transformer using IEC, ASTM and CEGB standards. The results in general, are categorized into two groups: crisp and fuzzy logics. The comparison between the two group indicates that in the cases that the crisp logic is not capable to diagnose the faults, the fuzzy logic is able to detect the faults with a specific0 reliability. The results of analysis of the data of three transformer using different standards, based on crisp and fuzzy logics, reveals the quality of the fuzzy logic in diagnosing the faults, especially for the cases that the crisp logic is not able to detect the fault.

TABLE IX
COMPARISON OF THE RESULTS OF DISSOLVED GAS ANALYSIS FOR THREE TRANSFORMER USING DIFFERENT STANDARDS BASED ON CRISP AND FUZZY LOGICS

	Standard	Transformer 1	Transformer 2	Transformer 3
Diagnosis using Crisp Logic	IEC	Thermal Fault with the temperature above 700^{oC}	Thermal increase with the temperature of 200^{oC} -300^{oC}	non diagnosable
	ASTM	Circulating currents between core and tank	Thermal increase with the temperature of 150^{oC} -200^{oC}	non diagnosable
	CEGB	Thermal Fault with the temperature above 700^{oC}	Thermal increase with the temperature of 150^{oC} -200^{oC}	non diagnosable
Diagnosis using Fuzzy Logic	IEC	Thermal Fault with the temperature above 700^{oC}	Thermal Fault with the temperature less than 150^{oC} with reliability = 0.15	Thermal Fault with the temperature less than 150^{oC} with reliability =0.5
	ASTM	Circulating current or electric arc with energy discharge	Thermal Fault with the temperature less than 150^{oC} with reliability =1	Thermal Fault with the temperature of 200^{oC} - 300^{oC}with reliability =1
	CEGB	Circulating current or electric arc with energy discharge	Increase in Temperature less than 150^{oc}	Thermal Fault with the temperature of 200^{oC} - 300^{oC}with reliability =0.8
Actual Fault		Thermal Fault with the temperature above 700^{oC} and Electric Arc	Increase in Temperature less than 150^{oc}	Thermal Fault with the temperature of 200^{oC} -300^{oC}

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