A Novel Approach for Oil-immersed High Voltage Power Transformer Dissolved Gas Analysis Diagnostic techniques

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ABSTRACT

This essay introduces and analyzes the dissolved gases in the insulating oil of power transformers. Analysis of soluble and free gas is one of the most commonly used troubleshooting methods for detecting and evaluating equipment damage. Although the analysis of oil-soluble gases is often complex, it should be expertly processed during maintenance operation. The destruction of the transformer oil will produce some hydrocarbon type gases. The development of this index is based on two examples of traditional evaluation algorithms along with fuzzy logic inference engine. Through simulation process, the results of the initial fractures in the transformer are obtained in two ways by the "Duval Triangle" and "Rogers ratios". In continue, three digit codes containing the fault information are created based on the fuzzy logic inference engine to achieve better results and eliminate ambiguous zones in common methods especially in Duval Triangle method. The proposed method is applied to 80 real transformers to diagnose the fault by analyzing the dissolved oil based on fuzzy logic. The results illustrate the proficiency of this new proposed algorithm. Finally, with utilization of a neural network the new practical inference function is derived to make the algorithm more usable in online condition monitoring.

Index Terms — **Power transformer, Fault diagnosis, DGA, Fuzzy Logic, neural network.**

1 INTRODUCTION

Power transformers as one of the most expensive network equipment, transmission and distribution of electric power are crucial. As a result, the monitoring of this equipment is very important in order to troubleshoot or prevent defects before damage to the equipment. Ensuring the transmission of electrical energy to the entire system without interruption and losing many loads, depends on reliable electrical equipment. Transformer is one of the primary electrical systems for increasing the voltage in transmission networks and then reducing it in distribution centers.

In the 1880s, when there was no transformer, transmission was carried out at low voltages and high current, causing a lot of losses, as well as near-consumer manufacturing centers. The unexpected failures in transformers can break down the electrical system, which can lead to huge economic losses. To avoid providing an unplanned system, periodic analysis is done on the transformer. Analysis of Transformers is more concerned with their insulation, mainly of insulating mineral oil (IMO) have been formed and oil as main function is to separate the insulation and cooling equipment. Since the 1960s, methods have been used to analyze the gases generated in insulating oil, which predicted the types of errors or defects in the transformer [1].

This applied paper is on the analysis of gases produced in mineral oils of power transformers. Through simulation, the results of the initial fractures in the transformer are obtained in two ways by the "Duval Triangle" and "Rogers ratios".

In this paper, three and four digit codes containing the fault information are created based on the fuzzy logic to achieve better results. The method is applied to 80 real transformers to diagnose the fault by analyzing the dissolved oil based on fuzzy logic and is approximated using the neural network.

2 DISSOLVED GAS ANALYSIS

The ratio of dissolved gases to the diagnostic basis was used by Mr. Dannenberg in 1970 to distinguish between electrical and thermal imperfections using six gases and four ratios [2]. After him, Rogers, inspired by the Thermodynamics Model, proposed the Rogers ratio method for the first time in 1973 [3], which improved in 1975 and 1977 [4]. This theory was analyzed in 1978, laboratory research, industrial tests, and theoretical evaluations, and then changed to standard IEC 60599.

DGA different ways using fuzzy logic in references [5, 6] proposed and developed. In reference [7] A DGA method with fuzzy learning has increased and compared with other conventional methods.

Table 1: Typical faults in power transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from incomplete impregnation,high humidity in paper, oil super saturation or cavitation, and leading to X-wax formation
D1	Discharges of low energy	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroids, adjacent disks or conductors of winding, broken brazing or closed loops in the core Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls Tracking in wooden blocks, glue of insulating beam, winding spacers. Breakdown of oil, selector breaking current
D2	Discharges of high energy	Flashover, tracking, or arcing of high local energy or with power follow-through Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs
T1	Thermal fault $t < 300$ °C	Overloading of the transformer in emergency situations Blocked item restricting oil flow in windings Stray flux in clamping beams of yokes
T2	Thermal fault 300 °C < t <700 °C	Defective contacts between bolted connections (particularly between aluminium busbar), gliding contacts, contacts within selector switch (pyrolitic carbon formation), connections from cable and draw-rod of bushings Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields Abraded insulation between adjacent parallel conductors in windings
T3	Thermal fault $t > 700$ °C	Large circulating currents in tank and core Minor circulation currents in tank walls created by a high uncompensated magnetic field Shorting links in core steel laminations

2.1 DOERNENBURG RATIO METHOD

The diagnostic theories use a set of combustible key gas ratios based on the dissolution principles as error indicators. These five ratios are:

Ratio 1 (R1) = CH_4/H_2
Ratio 2 (R2) = C_2H_2/C_2H_4
Ratio 3 (R3) = C_2H_2/CH_4
Ratio 4 (R4) = C_2H_6/C_2H_2
Ratio 5 (R5) = C_2H_4/C_2H_6 (1)

The Dorneenberg ratio method uses ratios 1, 2, 3, and 4. This method requires a significant level of gases to identify the method's validity.

The ratios should be compared to 1, 2, 3, and 4 and the constrained values, and the proposed error detection is presented in accordance with Table 2. Table 2 shows the limiting values of the ratio of gases dissolved in oil.[8]

Table 2: Ratios for key gases—Doernenburg

Suggested fault diagnosis	R1 CH_4/H_2		R2 C_2H_2/C_2H_4		R3 C_2H_2/CH_4		R4 C_2H_6/C_2H_2	
	Oil	Gas space	Oil	Gas space	Oil	Gas space	Oil	Gas space
1. Thermal decomposition	>1.0	>0.1	<0.75	<1.0	<0.3	<0.1	>0.4	>0.2
2. Partial discharge (low-intensity PD)	<0.1	<0.01	Not significant	<0.3	<0.1	>0.4	>0.2	
3. Arcing (high-intensity)	>0.1 to <1.0	>0.01 to <0.1	>0.75	>1.0	>03	>0.1	<04	<0.2

2.2 ROGERS RATIO METHOD

Table 3, show Rogers ratio [8] by the use of three gas ratios as C2H2/C2H4, CH4/H2 and C2H4/ C2H6 to indicate four possible faults diagnosis as normal unit, low energy density and arcing PD, arcing high energy discharge, and low temperature thermal.

Table 3: Rogers's ratios for key gases

Case	R2 C_2H_2/C_2H_4	R1 CH_4/H_2	R5 C_2H_4/C_2H_6	Suggested fault diagnosis	Fuzzy Code
0	<0.1	>0.1 to 1.0	<1.0	Unit normal	012
1	<0.1	<0.1	<1.0	Low energy density arcing PD	002
2	0.1 to 3.0	0.1 to 1.0	>3.0	Arcing High energy discharge	213
3	<0.1	>0.1 to <1.0	1.0 to 3.0	Low temperature thermal	012
4	<0.1	>1.0	1.0 to 3.0	Thermal <700C	022
5	<0.1	>1.0	>3.0	Thermal >700C	023

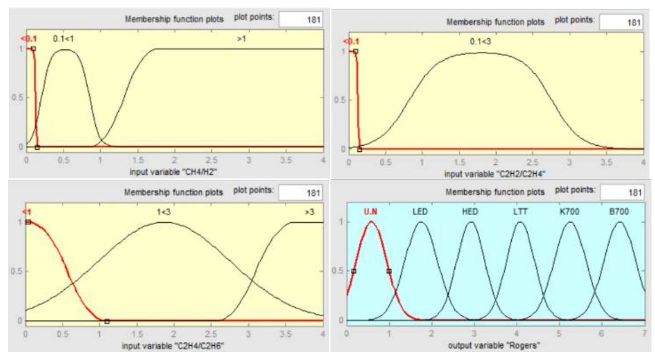

Figure 1: Membership functions of input and output variables Rogers fuzzy system

2.3 IEC STANDARD METHOD

This method is taken from the Rogers ratio method, except that the ratio of C_2H_6 / CH_4 is lost because it only represents the temperature range in the decomposition shown in Table 4. In this method, errors are divided into six different types.

Table 4: IEC GAS RATIO

Case	Faults	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial Discharge	NS	<0.1	<0.2
D1	Discharges of low energy	>1	0.1-0.5	>1
D2	Discharges of High Energy	0.6-2.5	0.1-1.0	>2
T1	Thermal Fault	NS	>1	<1
T2	Thermal Fault	<0.1	>1	<1
T3	Thermal Fault	<0.2	>1	>4

2.4 DUVAL TRIANGLE METHOD

This method has been stable and reliable for many years and its popularity is increasing. The Duval triangle, as shown Figure 2, determines what the problem is with the system. In this method, three gases (CH_4, C_2H_2, C_2H_4) are investigated.[9]

To use the Duval method, refer to Table 5, which includes the minimum concentration of L1 gas in ppm and the gas production rate G1 and G2 both in ppm per month. Among all gases produced in oil, at least one gas must be equal to or greater than the values of L1, and the gas production rate is equal to or greater than G2. If the values are greater than G1, a warning signal is sent from the equipment.

After all the conditions for using the method are met, the ratio of the percentage of each gas is calculated. To do this, the concentration of gas is divided by the total concentration of three gases in terms of concentration in ppm, as follows [9]:

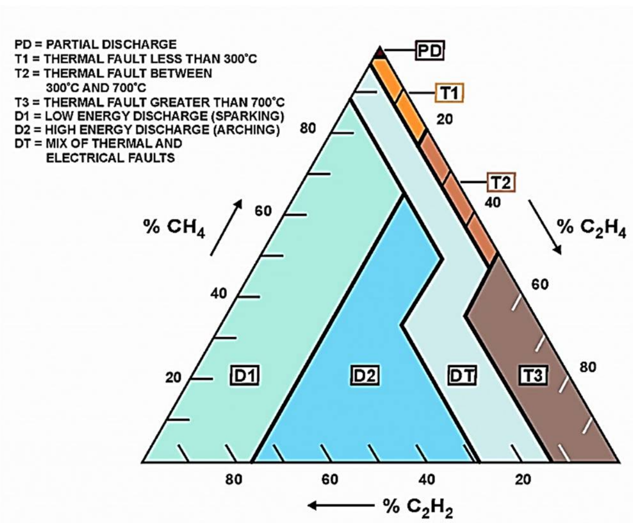

Figure 2: Duval triangle [10]

Table 5: The range of oil gases and the range of gases produced per month

Gas	L1(ppm)	G1(ppm / month)	G2(ppm / month)
H_2	100	10	50
CH_4	75	8	38
C_2H_2	3	3	3
C_2H_4	75	8	38
C_2H_6	75	8	38
CO	700	70	350
CO_2	7000	700	3500

$$\%CH_4 = 100*P1/ (P1+P2+P3)$$
$$\%C_2H_4 = 100*P2/ (P1+P2+P3)$$
$$\%C_2H_2 = 100*P3/ (P1+P2+P3) \quad (2)$$

To simplify the expressions, select P1 for methane gas (CH_4), P2 for ethylene (C_2H_4) and P3 for acetylene (C_2H_2). Duval has three percent of gas who becomes fuzzy logic controller with three inputs. Each entry memberships functions required to achieve the Rules of Procedure and an outlet with seven membership function that indicates the type of error detection by duval triangle are defined.

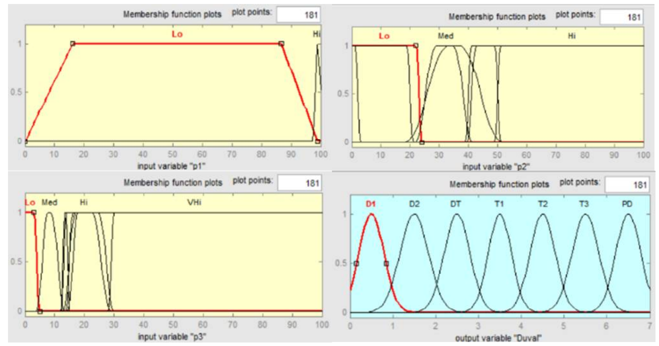

Figure 3: Membership functions of input and output variables duval triangular fuzzy system

3 FUZZY LOGIC INFERENCE ENGINE

Each method of error detection has advantages and limitations. A new approach has been introduced to advance benefits and reduce constraints. The proposed system is constructed by constructing a fuzzy logic controller with three fuzzy logic controllers combining two methods together to obtain more precision, plus natural gas fuzzy logic controllers.

The new technique of the fuzzy system consists of three steps:

Step one: The first new fuzzy controller, with the output of normal fuzzy controller constraints, has five inputs that contain five gases (H_2, CH_4, C_2H_6, C_2H_2, and C2H4) in ppm, and each input has two low and high membership functions for reaching the natural gas level. The limitations of gases in the duval triangle method are shown in Table 5, which we have defined with regard to other factors affecting the fuzzy network. The natural gas fuzzy controller has an output with two membership functions, which indicates the Normal and Fault are shown in Figure 4.

Step Two: Each of the two fuzzy methods (Rogers and Duval triangle) receive five gas as inputs to deliver the results of their error type;

Step three: Includes a fuzzy group controller that has three inputs, two of which result from an error type of two fuzzy methods and its next input, the output of the fuzzy controller of the first stage, which indicates an error or no error in the system.

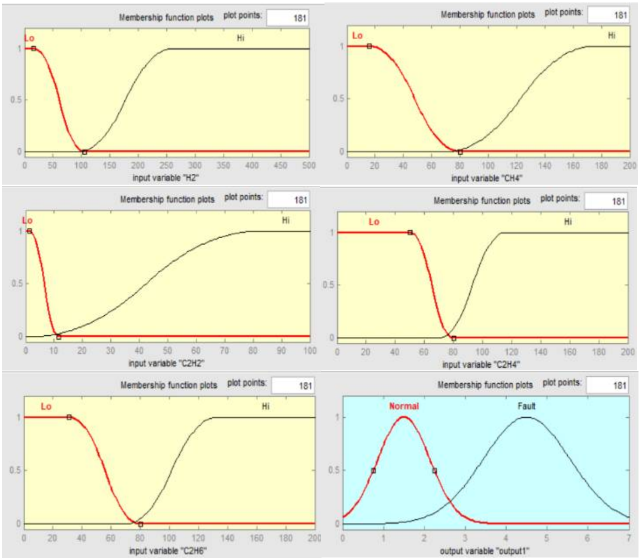

Figure 4: The membership functions of the input and output variables of the fuzzy diagnostic system

If the defect controller is in normal position, the output of the Rogers and Duval fuzzy systems will not be examined at all, and the final output will show normal mode; however, the output of those items will also be checked and displayed, and the probability of an error occurring at the output. The final fuzzy system can be picked up. However, if the fault diagnostic controller is in error mode then the final fuzzy controller will examine the output of the two other fuzzy systems and, after examining the defined conditions, declares the type of error that is between 0 and seven, and according to Figure 5 Interpreted and the type of error is detected.

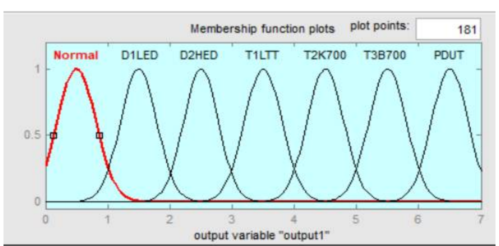

Figure 5: The final fuzzy system output membership functions

The fuzzy system designed in Simulink MATLAB will be in accordance with Figure 6.

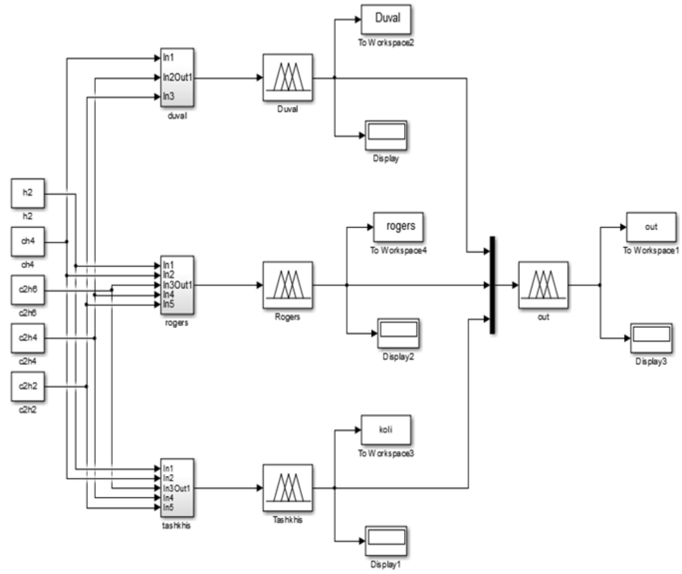

Figure 6: The fuzzy system designed in Simulink

4 NEURAL NETWORK

Since it was necessary to run the MATLAB program in order to run the fuzzy logic program, we decided to approximate the system using the neural network. After training and testing the neural network, we were able to obtain an equation for calculating the output of a fuzzy system that can be interpreted and analyzed using Figure 5. In addition to simplifying the work of users, this equation makes it possible to use the designed program for the power industry as well.

Figure 7 shows the neural network is designed; Figure 8 shows A comparison between the actual values and output neural network and Figure 9 shows Neural network error.

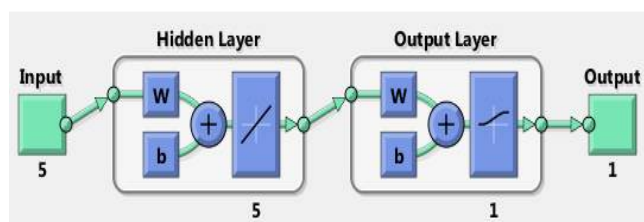

Figure 7: designed neural network

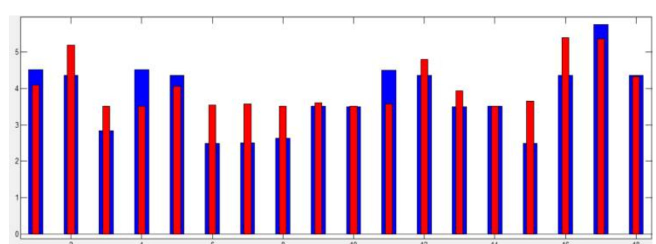

Figure 8: A comparison between the actual values and output neural network

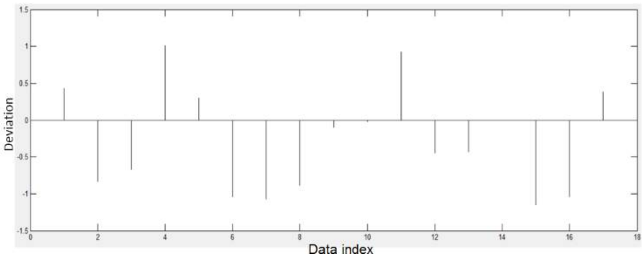

Figure 9: Neural network error comparing to real test data

The mathematical approximated formula is obtained as below:

$$y = \log[9.057x_1 + 0.694x_2 + 0.491x_3 + 1.833x_4 + 1.261x_5 - 3.2]\text{-}3.5 \quad (3)$$

Where x1 to x5, respectively illuminate h2, ch4, c2h6, c2h4 and c2h2 values; y represents the output of the fuzzy system of internal transformer error after the DGA, and interpreted according to Figure 5.

5 DISCUSSION

After preparation and compilation, the software was tested with data containing 80 different real conditions of oil gas, and the results were compared with manual calculations. The data used for samples were from transformers oil under different conditions. A summary of the results as an appraisal analysis of the program is presented in Table 6.

Examining the results and comparing with the actual results shows that in cases where the values of gases are near the boundaries determined by the duval triangle model, this method is wrong and cannot properly detect these errors due to the absence of normal operation mode of transformer. And this may cause further problems for the transformer in the future, and also lessen the popularity of the Duval triangle method. On the other hand, Rogers's method also indicates that an unknown or out-of-range error is present in some cases when the ratios are not from its range. Due to these problems, it was tried to provide a method that improves the performance of the dissolved gases analysis, thus combining the two methods of Duval triangle and Rogers ratios, which are more popular among the experts than other methods; We also added the fuzzy logic inference engine to increase the efficiency of the method. It is also approximated using proper neural network and the obtained formula is useable easily in the common electrical industry analysis software.

That fuzzy inference increases the performance and reduces human factor in error detection process. Figure 6 shows the designed fuzzy system in Simulink of MATLAB.

6 CONCLUSIONS

The output agreement of the proposed model with real errors in a transformer has been tested using 80 DGA samples from transformers installed in Iran with known error types and it has been observed that in all cases the proposed model accurately and accurately corrected the error. Typical methods are distinguished individually. Of course, although the model is ready to detect a fault, in some instances excessive loss of oil and cellulose can interfere.

The proposed model reduces the time to calculate and analyze the oil transformer errors using the DGA system; provides more precise results for the detection of the transformer initiator error, and reduces the human error in interpreting the error in the DGA system.

Table 6: DGA results and fuzzy logic model output

Sample	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	Duval	Duval Fuzzy	Roger	Roger Fuzzy	FUZZY
1	200	205.9	250	740	1	T3	T3	U.T	K700	T2K700
2	300	112.25	180	360	95	DT	DT	U.T	HED-LTT	D2HED
3	56	334.1	75	32	31	DT	DT	U.T	HED-LTT	D2HED
4	33	7.882	6	5.3	0.2	T2	T2	NORMAL	NORMAL	NORMAL
5	176	652.9	47.7	75.7	68.7	DT	DT	U.T	HED-LTT	D2HED
6	70.4	198.9	28.9	241.2	10.4	T3	T3	B700	B700	T3B700
7	162	21.92	5.6	30	44	D2	D2	PD	HED	D2HED
8	345	37.6	27.5	51.5	58.75	D2	D2	PD	HED-LTT	D2HED
9	181	0.574	210	528	0	T3	T3	U.T	LTT	T2K700
10	172.9	205.9	172.9	812.5	37.7	D1	T3	U.T	B700	T3B700
11	2587.2	112.25	4.704	1.4	0	PD	PD	U.T	LED	PDUT
12	1678	334.1	80.7	1005.9	419.1	DT	DT	PD	HED	D2HED
13	206	7.882	74	612.7	15.1	T3	T3	U.T	HED	T2K700
14	180	652.9	75	50	4	T1	T1	U.T	K700	T2K700
15	34.45	198.9	3.19	44.96	19.62	DT	DT	U.T	HED-LTT	D2HED
16	51.2	21.92	5.1	52.8	51.6	D2	D2	PD	HED	D2HED
17	106	37.6	4	28	37	D2	D2	PD	HED	D2HED
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78	180.85	0.574	0.234	0.188	0	T2	T2	U.T	LED	T2K700
78	27	205.9	42	63	0.2	T2	T2	U.T	K700	T2K700
80	138.8	112.25	6.77	62.8	9.55	DT	DT	PD	HED	D2HED

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