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Make Use of DGA to Carry Out the Transformer Oil-Immersed Paper Deterioration Condition Estimation with Fuzzy-Logic

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Abstract

Remaining Life of the oil-immersed transformer is decided due to deterioration of the winding insulation paper (WIP). The DGA method is conventionally used to estimate the WIP deterioration status condition. This paper presented the four status conditions assessment of paper deterioration for oil-immersed transformer using fuzzy-logic (FL). In this paper the correlation between accumulated values of carbon dioxide (CO_2) and carbon monoxide (CO) with insulation resistance in oil-filled power transformers is studied using FL. The authors have estimated the insulation paper deterioration condition using proposed method for 20 transformers or more. As a result, appropriate maintenance scenario can be planned.

Keywords: Transformer, Dissolved gas analysis, Insulation paper, Fuzzy-logic;

1. Introduction

According to viewed historical data, a power transformer is expected to operate satisfactorily up to 40-45 years. As per latest trends, each power transformer needs special apparatus to keep continuous guard on its operation & health of insulations [20]. With current cost-benefit calculations, the user is forced to perform maintenance that will bring a further extension of the transformer life. The maintenance can only be based on on-site and off-site monitoring with extended analytical and electrical tests that can define the service condition of the transformer and predict its further life expectancy. It has been observed that highly loaded generator and furnace transformers show a more accelerated aging in comparison to grid units. It is not unusual that older transformers have 3 to 4% humidity in the solid insulations.

The life of a transformer is mainly dependent on the life of its solid insulation and the life-limit is determined by the thermal degradation of the winding paper. The Kraft paper decreases in tensile strength with the progress of aging and, at some point, can no longer withstand the short circuit stresses. A traditional and significant parameter of paper degradation is the degree of polymerization (DP). The mechanism of paper degradation is complex and strongly dependent on the operating conditions. Degradation occurs by the cleavage of the 1, 4-glycoside bond between two glucose monomers present in paper insulations. These chain scissions result in the lowering of the DP and a decrease in tensile strength. Typical byproducts that are detectable in oil are also formed; these are carbon monoxide (CO), carbon dioxide (CO_2), detectable by gas-in-oil analysis, as well as furans compounds [20].

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There are several detailed literature surveys on cellulosic aging [1-8], [11]. Most experiments, however, have been carried out at temperatures >100°C because of the shorter reaction times under laboratory conditions. The aging products, as a result of typical operating transformer temperatures, have not been investigated in detail. Furthermore, the development of aging is quite different in open and closed systems. Closed systems do not allow the escape of moisture and other byproducts. It is likely that even a free-breathing transformer follows closer the behavior of closed, rather than that of open, systems, especially in respect to moisture. The aging is strongly influenced by temperature, moisture, air, and electrical stress [10]. It is well known that the aging of thermally upgraded paper is different from the aging of normal Kraft paper [5].

2. Material and Methodology

2.1 Power Transformer Units

Twenty five transformers from seven substations of the Himachal Pradesh Electricity Board (HPSEB) in India are used. The data is collected from the transformers' maintenance records of the operation and maintenance department and oil samples are collected as per ASTM standard. The transformers have different service periods and aging conditions. The transformers ratings ranges from 6.3-52MVA and their rating voltage ratios are 132/33/11 KV.

2.2 CO_2 and CO Accumulated Total Gas Values

CO_2 and CO total gas values are obtained as a part of DGA. The status conditions based on accumulated values of CO_2 and CO is given as per the IEEE Standard C57.104™ *Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers* [4]. These accumulated dissolved gas levels provide four status conditions for estimation the paper deterioration: Normal Operation, Modest Concern (investigate), Major Concern (more investigation), and Imminent Risk (nearing failure). For each status condition, the CO_2 and CO levels in ppm are given as below:

Table 1. Paper Status Condition Using CO and CO_2

CO_2	CO	Condition
X_1=0-2500	Y_1=0-350	Normal Operation (NO)
X_2=2500-4000	Y_2=351-570	Modest Concern (MCI)
X_3=4001-10,000	Y_3=571-1400	Major Concern (MCMI)
X_4=>10,000	Y_4=>1400	Imminent Risk (IRF)

2.3 CO_2/ CO Ratio

CO_2/CO ratio test is conducted as a part of DGA. It gives an indication of the paper insulation involvement in faults and carbonization, thus, the deterioration of cellulose. According to the IEC 60599, if the CO_2/CO ratio is less than 3, this indicates cellulose deterioration involvement. An off line oil sample is taken from the transformer main tank and the chromatographic analysis is performed to analyze the dissolved gases in the transformer.

Table 2. Test Results of Various Samples

Sample No.	MVA Rating	BDV (KV)	DGA Test Results						
			H_2	CO_2	CO	C_2H_4	C_2H_6	CH_4	C_2H_2
1	6.3	24.2	7	5315	662	50	32	138	2.5
2	6.3	23.2	1879	198	06	36	05	29	521
3	16/20	33.9	6	3089	405	17	10	17	<0.5
4	10.5	55.5	07	1178	193	05	03	04	<0.5
5	16	32.9	18	3141	158	08	02	02	0.5
6	31.5	40.1	<5	4811	480	12	07	07	<0.5
7	31.5	48.7	<5	1936	97	05	05	07	<0.5
8	52	68.1	14840	433	42	485	17	290	4895
9	52	68	16	5004	935	28	05	12	29
10	52	69.2	1866	229	10	111	02	64	1265

The chromatographic analysis is sensitive to atmospheric condition; therefore, it is highly recommended to perform such test away from interfering conditions like sources of CO_2. The DGA is performed using the IEC 567 method.

3. Fuzzy-Logic Based Methodology

All Fuzzy-Logic (FL) is a relatively new artificial intelligence technique. FL means approximate reasoning, information granulation, computing with logical words and so on. Fuzzy systems are rule-based systems that are constructed from a collection of linguistic rules. FL is a convenient way to map an input space to an output space. It provides mathematical strength to the emulation of certain perceptual and linguistic attributes associated with human cognition. The theory of fuzzy logic provides an inference mechanism under cognitive uncertainty. This view of network as a parameterized function will be the basis for applying standard function optimization methods to solve the problem of neural network training.

3.1 Expert System for Transformer's Oil-immersed paper Deterioration Estimation

The schematic diagram of fuzzy logic based transformer insulation paper deterioration estimation (FLPDE) expert system is shown in Fig.1. FLPDE is a novel fuzzy-based approach that deals with heterogeneous data of both linguistic and numeric types, imprecise, vague in-formation, and concepts encountered in the mechanical-fit process and facilitate the expression of the reasoning process of an experienced observer with minimal rules.

The Fuzzy Logic Transformer insulation diagnosis process represents a fuzzy-logic-based complete transformer diagnosis process comprising the following three phases:

phase I: tentative selection of CO_2 , and CO;

phase II: mechanical-fit process;

phase III: estimation and optimization of insulation paper status conditions.

A general schematic of FLPDE representing the second phase is shown in Fig. 1. It involves the following phases:

1) Fuzzification;
2) Knowledge representation;
3) Inference scheme;
4) Defuzzification.

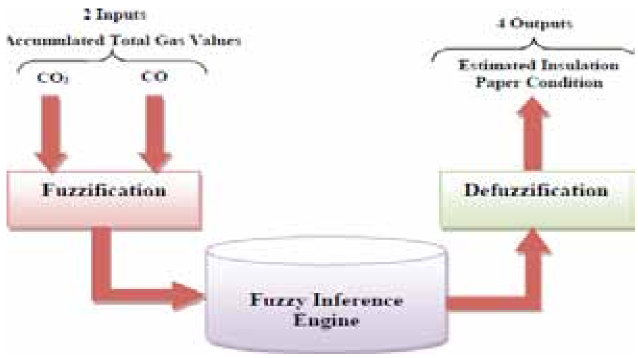


Fig. 1: General scheme of FLPDE

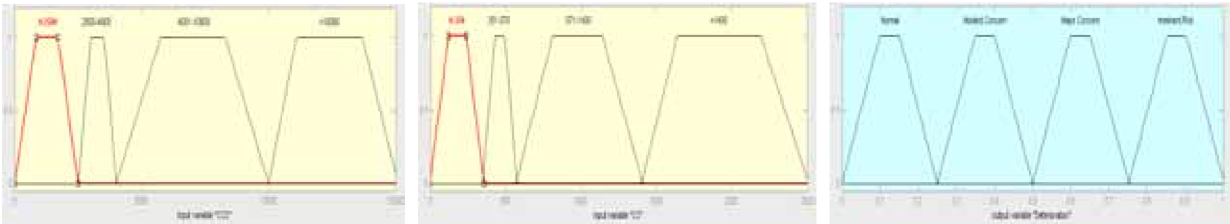
In Section "3.2", membership function of input and output variables for fuzzy FLPDE expert system are discussed. Section "3.2" also presents the fuzzy rules based paper deterioration result's graph. Section 4 and 5 describes the simulation results and conclusion respectively.

3.2 Input and Outputs of Fuzzy-Logic System

CO_2 and CO in transformer is useful in finding out the suitable oil-sampling interval based on the health condition of the transformer so as to compensate the conflict between excessive cost due to over sampling and neglected danger owing to long sampling period.

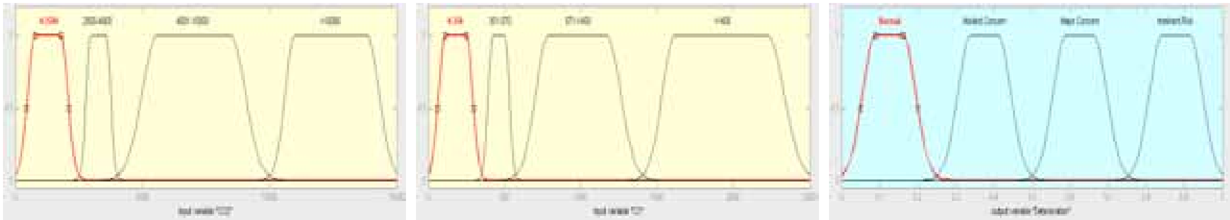
Although "CO_2 and CO accumulated total gas values" and "CO_2/CO ratio" methods are widely used in solving insulation deterioration diagnosis problem, but in the certain cases, it is very hard to determine the correct group of the CO_2 and CO values especially when the CO_2 and CO value fall near the boundary line as shown in the CO_2 and CO rules set in Table 1. The fuzzy logic technique is advantages in solving this problem.

For the insulation paper diagnostic method, Membership functions (MF) for input variables are established based on the variation of CO_2, and CO as shown in Fig. 2(a-b), 3(a-b) and 4(a-b). The membership functions for the output variables (expected insulation paper deterioration condition) are shown in Fig 2(c), 3(c), and 4(c).



(a) (b) (c)

Fig. 2: Trapezoidal membership functions (trapmf): (a) input variable of CO_2; (b) input variable of CO; (c) output variable of WIP Condition.



(a) (b) (c)

Fig. 3: Gaussian membership functions (gauss2mf): (a) input variable of CO_2; (b) input variable of CO; (c) output variable of WIP Condition.

(a) (b) (c)

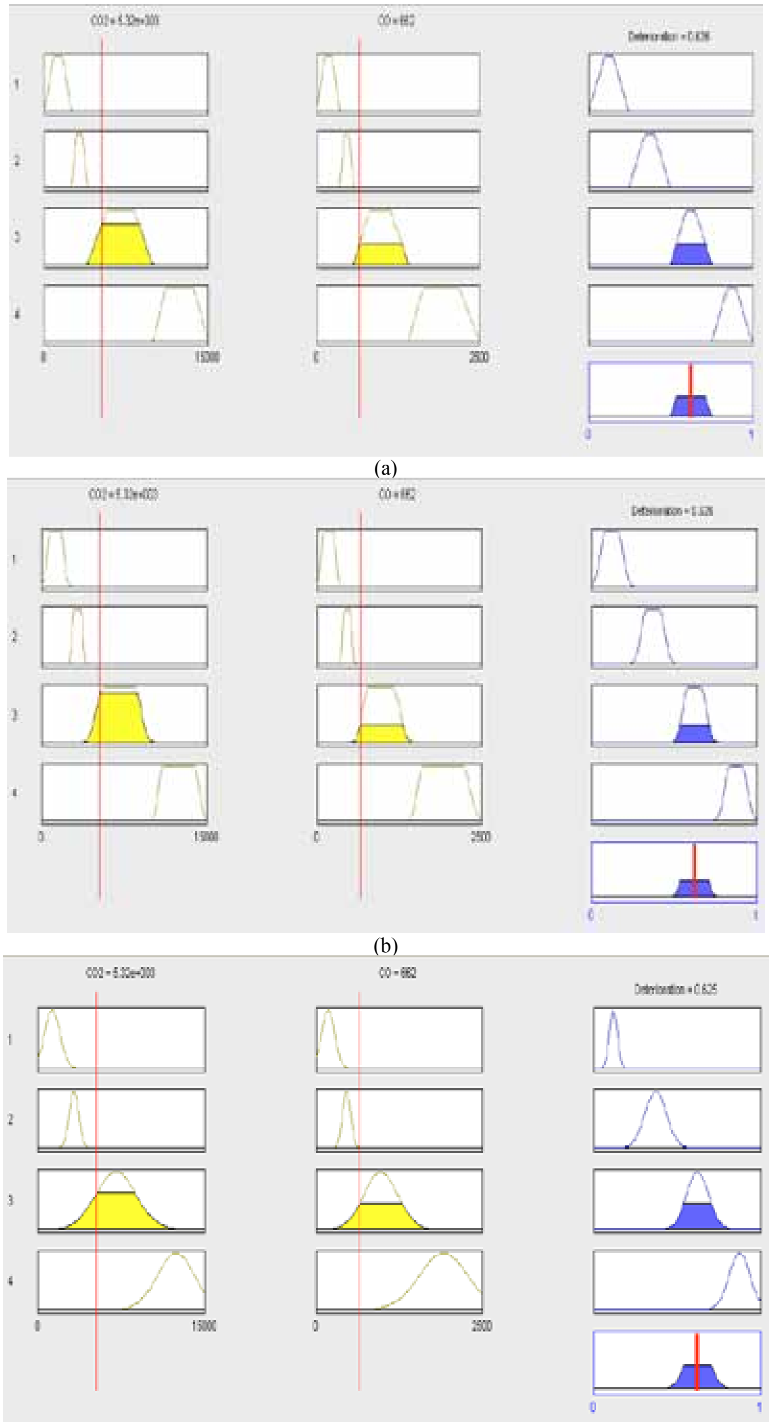
Fig. 4: Gaussian membership functions (gauss): (a) input variable of CO_2; (b) input variable of CO; (c) output variable of WIP Condition.

Table 3. Fuzzy logic rules for transformer insulation paper deterioration condition estimation

	Y_1	Y_2	Y_3	Y_4
X_1	NO	N	N	N
X_2	N	MCI	N	N
X_3	N	N	MCMI	N
X_4	N	N	N	IRF

Where; X_1, X_2, X_3, X_4 and Y_1, Y_2, Y_3, Y_4 are the fuzzy input variables. N denotes the Null condition.

Based on the experimental results, a set of fuzzy rules relates the input variables to the output are developed as shown in Table 2. The expected health condition for transformer insulation paper using input variables is shown in Fig. 5.



(a)

(b)

(c)

Fig. 5: Test results of fuzzy based WIP deterioration conditions with (a) triangular membership function; (b) Gaussian membership functions (gauss2mf); (c) Gaussian membership functions (gauss)

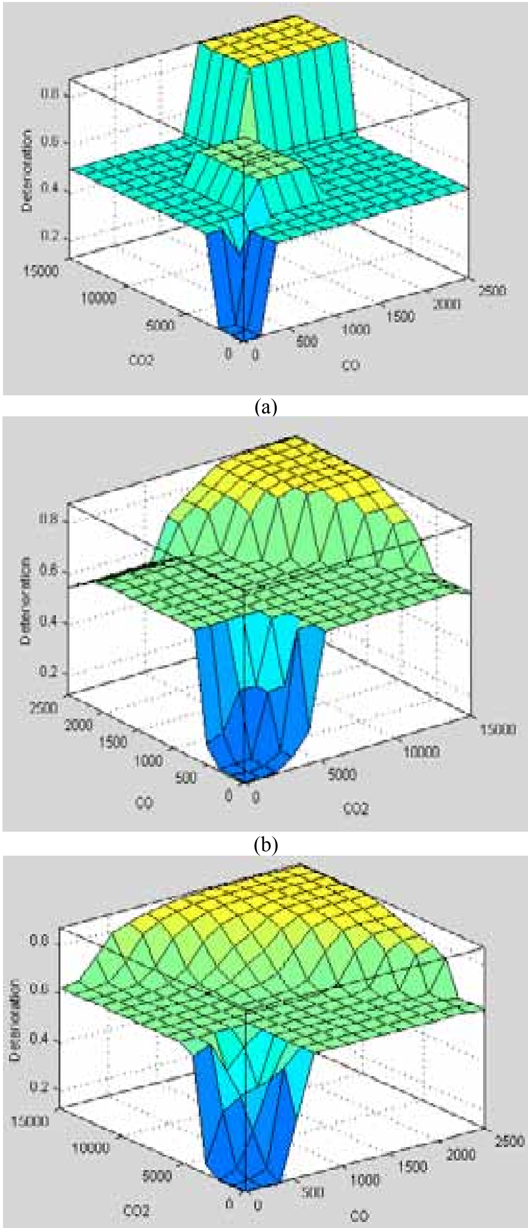


Fig. 6: Surface graph-Spectrum-WIP deterioration conditions with (a) triangular membership function; (b) Gaussian membership functions (gauss2mf); (c) Gaussian membership functions (gauss).

4. Results and Discussion

Using the Fuzzy-logic, a number of 11–132 kV power transformers of Himachal Pradesh State Electricity Board (HPSEB), India were diagnosed and some typical results are given in Table 3. These results are taken by using Kalman Transport-X DGA analyzer. For this method, four status conditions of paper deterioration are determined by choosing the highest degree of membership value obtained from the fuzzy inference rules. The status conditions of paper deterioration can be classified into the linguistic variable based on the degree of membership function as shown as Table 4.

Table 4. Four Estimated Condition by Fuzzy Logic for transformer diagnosis

Degree of Membership of Fuzzy output Result for status condition	
Normal Operation (NO)	<0.20
Modest Investigate (MCI)	0.30-0.45
Major Investigate (MCMI)	0.61-0.68
Nearing Failure (IRF)	>0.7

It can be seen from sample no. 1-4, 7-10 that the new method is generally in agreement with ANSI/IEEE method for transformers of deterioration of oil immersed paper condition. Compared with ANSI/IEEE C57.104 method, the fuzzy logic method also has some advantages. For example, due to no matching condition, five transformers could not be diagnosed by the ANSI/IEEE method but are diagnosed by the fuzzy logic method, as shown in Table 5 no. 5–6 for some typical results so we concluded that no. 5 required MCI and no 6 required MCMI.

TABLE 5. TEST RESULTS OF VARIOUS SAMPLES USING FUZZY LOGIC

Sample No.	**DGA Test Results**			**WIP Deterioration Condition as per IEEE Std. C57.104**	**Estimated Condition by Fuzzy Logic**		
	CO_2	**CO**	**CO_2/CO**		**Using Trapezoidal Function**	**Using Gauss2mf Function**	**Using Gaussmf Function**
1	5315	662	8.03	Major Concern	0.626	0.626	0.625
2	198	06	33	Normal Condition	0.125	0.127	0.127
3	3089	405	7.63	Modest Concern	0.375	0.375	0.399
4	1178	193	6.10	Normal Condition	0.125	0.125	0.139
5	3141	158	19.9	**No match**	**0.25**	**0.259**	**0.253**
6	4811	480	10.0	**No match**	**0.5**	**0.628**	**0.622**
7	1936	97	19.9	Normal Condition	0.125	0.125	0.127
8	433	42	10.3	Normal Condition	0.125	0.125	0.128
9	5004	935	5.35	Major Concern	0.626	0.626	0.625
10	229	10	22.9	Normal Condition	0.125	0.127	0.127

In some cases, the deterioration of insulating paper may be only at the early stage or intermittent which did not produce sufficient gases to give a stronger indication. However, such information obtained should be useful for future trend analysis.

5. Conclusion

The DGA is a very efficient tool for diagnosing incipient failure condition in oil-filled electrical equipment. The gas ratios and relative proportions of gases can be used to diagnose the failure condition and improve the accuracy of insulation deterioration diagnosis. This paper has been described the oil-immersed paper deterioration condition assessment for transformer using fuzzy logic and ensemble technique. The effectiveness of the proposed method has been shown by numerical simulation using actual measured data. The authors have estimated the insulation paper deterioration condition using proposed method for 20 transformers or more. As a result, appropriate replacement time of transformer and appropriate maintenance scenario can be planned.

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