Fuzzy Logic Expert System for Incipient Fault Diagnosis of Power Transformers

Zakir Husain

Department of Electrical Engineering
National Institute of Technology Hamirpur, Himachal Pradesh, 177005, India

Abstract: Condition monitoring of power transformers improves the security and reliability of an electrical power system. It protects the transformers from failures, and avoids huge revenue loss to utilities and customers. The fault diagnosis of transformers is carried out by concentrations of several dissolved gasses. An accurate fault diagnosis of transformers has been a critical problem for diagnostic experts of transformers. In this article, a novel fuzzy logic model has been proposed to determine the transformer incipient faults. It incorporates the information obtained from dissolved gas analysis test. Further, the proposed model also incorporates conventional fault diagnosis methods viz. Duval Triangle, Doernenburg, Rogers, and IEC ratio code methods. The proposed fuzzy logic models short out the problems occur in the conventional fault diagnosis methods of transformers.

Keywords: Transformer, dissolved gasses, fuzzy logic, incipient fault, diagnosis.

1. Introduction

Power transformers are vital devices in substations. These devices play a significant role in electricity transmission and distribution systems. Abnormal conditions of transformers increase the aging rate. Finally, it may lead to transformer failure. As a result a huge revenue loss is occurred to utilities and customers [1]. Hence, the incipient fault diagnosis transformer has gained a great role in recent days [2]. From the literature, it is found that the transformers fault diagnosis has been majorly achieved using the data obtained from liquid and solid insulations [3]. Several gasses are dissolved in to the transformer oil due to the aging of these solid and liquid insulations. These gasses are normally measured by the dissolved gas analysis (DGA) which is a highly significant test of transformers. These dissolved gas concentrations are further used to determine the type of incipient fault present within the transformers [4]. Various fault diagnosis methods including Key gas, Duval Triangle, Rogers ratios, modified Rogers ratios, Dornenburg ratios and IEC/IEEE ratio code methods have been developed. In addition to DGA, several other tests namely, water content, break down voltage (BDV), flash point (FP), tensile strength (TS), degree of polymerization (DP) and furan content (FC) of solid insulation, interfacial tension (IFT) tests etc. have been used to determine the current health condition of the transformers [3-6]. All these tests have their own significance in evaluating the current health condition of the transformers. For the past three decades, large number of fuzzy logic models has been proposed based several diagnostic tests data, to evaluate the overall health condition and type of incipient fault present in the transformers [7]. Fuzzy logic is highly useful tool to determine the type of incipient fault present in power transformers [8]. It is a logical system which provides a very convenient method to map the input to the output through linguistic rules formed from human understanding rather than stringent mathematical models [9]. Fuzzy logic can combine the various diagnostic tests data and the practical knowledge of transformer diagnosis experts [10]. Moreover, FL is helpful for managing uncertain and vague information and hence fuzzy logic is an ideal tool for managing imprecise and vague information in the real world [11]. Fault Diagnosis of transformers determines the type of fault based on dissolved gasses. Although the fuzzy models proposed earlier have their own importance in determining the incipient faults of transformers, however none of them determine all types of faults including multiple incipient faults of the transformers [12]. An

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accurate fault of transformers not only depends on one or two conventional DGA methods but also on several other advanced methods including Ducal Triangle method [13]. Consequently, there is a great need for a new approach which determines the type of incipient fault correctly. This task has been addressed in the present paper.

In this paper, a new fuzzy logic (FL) model is proposed to determine the type of incipient fault present in the transformers based dissolved gasses concentrations. It relies on DGA conventional interpretation methods including Rogers, IEC, Dornenburg and Duval Triangle methods. It overcomes the shortcomings of each of the conventional DGA interpretation methods. The proposed model can recommends the preventive necessary actions based on the type of incipient fault of transformers. Fifty transformers oil samples of different ratings operated by Himachal Pradesh State Electricity Board, India were examine and prove the reliability, validity and efficacy of the proposed fuzzy logic model.

2. Fuzzy Logic Approach

Various phases of fuzzy logic models are detailed in below sections.

A. Generation of Membership Functions and Fuzzification

A curve which specifies how a given input is correlated with a degree of membership (DOM) is called as MF. Is has values between 0 and 1. MF has several forms viz. sigmoidal or trapezoidal, triangular, Gauss2 and Gaussian [13, 14]. Popular MF is Trapezoidal MF, shown in Figure 1. It is computed by using equation (1).

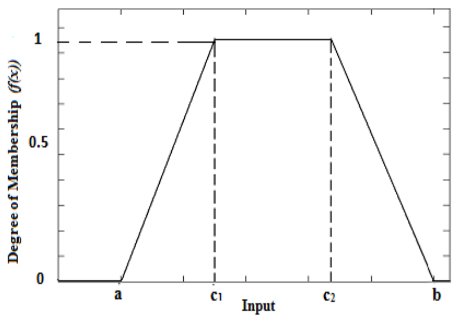

Figure 1. A trapezoidal MF.

$$\textit{Membership function} = \max\left\{\min\left(\frac{x-a}{c_1-a}, 1, \frac{b-x}{b-c_2}\right), 0\right\} \quad (1)$$

where, input variable is x, the minimum and maximum limits of the trapezoidal MF are a and b. Centers of the MF are c_1 and c_2 [15]. MF attains a maximum DOM whenever the input is placed between c_1 and c_2. Similarly, if inputs lie between a and c_1, and between c_2 and *b, the* DOMs values may present between 0 and 1.

B. Fuzzy inference

The procedure which maps the inputs and output by expert rules is called as fuzzy inference. In this research paper, Mamdani maximum–minimum fuzzy inference method has been utilized [16]. This scheme evaluates the output MF based on various expert rules between the inputs and the output. Moreover, it truncates the MF of the output at its minimum degree of membership.

C. Defuzzification

A non-crisp value which is obtained from the MF of the truncated output is computed in defuzzification step of FL method. In this research work, defuzzification has been done by widely used center of gravity method (COG) method. This method calculates the centroid of the truncated output MF (Z_0) [17], and given in (2).

$$Z_0 = \frac{\int z.\mu(z)\,dz}{\int \mu(z)\,dz} \tag{2}$$

In (2), the output variable is z and $\mu(z)$ is the degree of membership of the truncated MF.

3. The Proposed Fuzzy Logic based Transformer Incipient Fault Diagnostic Model

The proposed overall incipient fault diagnosis model includes various fuzzy logic models utilizing conventional DGA methods. The model determines the type of incipient fault present within the transformer oil. Each of all these sub-models is presented in this section.

A. The Proposed Fuzzy Logic Model for Incipient Fault Diagnosis using Doernenburg Method

In this method fault identification is based on gas concentration ratios such as CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2 (Table 1) which can be used to identify thermal faults, corona discharge and arcing [18]. The applicability of this method depends on individual key gas (H_2, C_2H_2, C_2H_4, C_2H_6, CH4) concentration in a way that at least one of the gases needs to be double in concentration than the specified limit. Doernenburg Ratio Method (DRM) can be found in IEEE C57.104-2008 guide. If all these four ratios fall within predetermined values then a specific fault can be identified. In some cases ratios does not lie in predetermined values due to incomplete ratio ranges which results in 'no interpretation' of fault [13]. DGA test results of different fifty oil filled transformers rated 11/0.43 kV, 630 kVA are given in Table 2.

Table 1. Doernenburg Ratio Method [13].

Case	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2	Fault Type
1	>1	<0.75	<0.3	>0.4	Thermal decomposition
2	<0.1	NS	<0.3	>0.4	Partial discharge (low-intensity PD)
3	>0.1,<1	>0.75	>0.3	<0.4	Arcing (high-intensity PD)
NS - Not significant					

In the present proposed incipient fault model using conventional Doernenburg Ratio Method, the input membership functions shown in Figure 2 are designed based on the four gas ratios given in Table 1 (columns 2 to 5). Similarly the output MFs seen in Figure 3 are designed based on column 6 of Table 1. The fuzzy logic expert rules relied on output and input MFs are given in Figure 4.

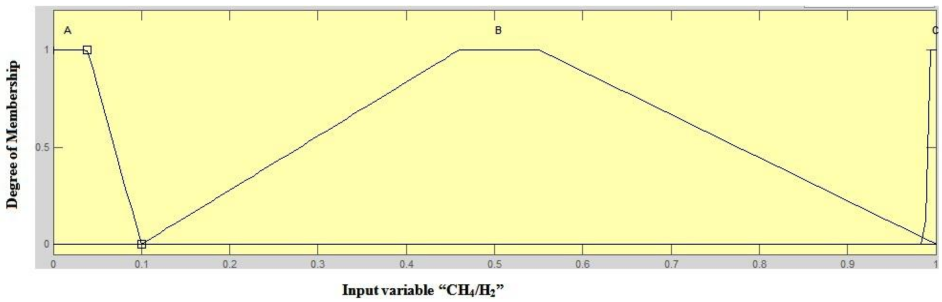

Figure 2. Input MFs for the proposed FL model F1.

Table 2. Dissolved gas analysis test results.

Sample Number	H_2 (ppm)	C_2H_4(ppm)	CH_4 (ppm)	C_2H_2 (ppm)	C_2H_6 (ppm)
1	19.3	19	103	0.6	159
2	497	151	230	122	51
3	615	102	200	68	42
4	594	130	230	102	44
5	27	2.4	30	0.1	23
6	38	28	55	0.1	22
7	30	4.1	22	0.1	14
8	23	10	63	0.3	54
9	2.9	0.3	2	0.1	1.5
10	4	4.2	99	0.1	82
11	56	928	286	7	96
12	78	353	161	10	86
13	21	47	34	62	5
14	50	305	100	9	51
15	120	23	17	4	32
16	172	812	335	37.8	171
17	181	28	262	0.1	41
18	27	63	90	0.2	42
19	160	96	130	0.1	33
20	180	50	175	4	75
21	<5	11	42	<0.5	38
22	8	12	42	<0.5	28
23	7	12	44	<0.5	28
24	9	11	46	<0.5	26
25	<5	2	3	<0.5	3
26	7	65	25	62	8
27	<5	7	5	<0.5	5
28	<5	13	6	<0.5	4
29	<5	13	11	<0.5	17
30	<5	30	11	<0.5	12
31	<5	25	51	<0.5	45
32	<5	10	50	<0.5	59
33	<5	13	5	<0.5	5
34	<6	15	65	<0.5	68
35	<5	11	51	<0.5	85
36	<5	12	52	<0.5	54
37	<5	8	6	<0.5	4
38	41	110	45	147	11
39	<5	7	10	<0.5	6
40	<5	9	7	<0.5	3
41	<5	8	11	<0.5	4
42	<5	7	8	<0.5	4
43	<5	7	4	<0.5	5
44	<5	11	<1	<0.5	10
45	<5	7	5	<0.5	5
46	505	817	256	881	82
47	5	10	87	<0.5	351
48	5	33	136	<0.5	1105
49	<5	21	113	<0.5	750
50	<5	12	18	<0.5	16

Table 3. Outputs of the conventional Doernenburg ratio method and the proposed FL model F1.

Sample number	C_2H_2/C_2H_4	CH_4/H_2	C_2H_6/C_2H_2	C_2H_2/CH_4	Output of conventional Doernenburg ratio method	Output of proposed Fuzzy model F1
1	0.0315	5.336	265	0.005	T	T,0.0439
2	0.807	0.4627	0.41	0.5	UD	UD,0.5
3	0.666	0.3252	0.61	0.34	UD	UD,0.5
4	0.7846	0.3872	0.43	0.4	UD	UD,0.5
5	0.0416	1.11	230	0.003	T	T,0.04
6	0.00357	1.45	220	0.001	T	T,0.0439
7	0.0243	0.733	140	0.004	UD	UD,0.5
8	0.03	2.739	180	0.004	T	T,0.044
9	0.333	0.689	15	0.05	UD	UD,0.5
10	0.024	24.75	820	0.001	T	T,0.0443
11	0.0075	5.12	13.7	0.02	T	T,0.0457
12	0.0283	2.064	8.6	0.06	T	T,0.0446
13	1.32	1.62	0.08	1.8	HEPD	HEPD,0.25
14	0.0295	2	5.66	0.09	T	T,0.044
15	0.1739	0.1416	8	0.23	UD	UD,0.5
16	0.04655	1.947	4.52	0.11	T	T,0.0435
17	0.0036	1.4475	410	0.003	T	T,0.0459
18	0.0032	3.33	210	0.003	UD	UD,0.5
19	0.00104	0.8125	330	0.0007	UD	UD,0.5
20	0.08	0.972	18.75	0.02	UD	UD,0.5
21	0.045	8.4	76	0.01	T	T,0.0435
22	0.041	5.25	56	0.01	T	T,0.0435
23	0.041	6.28	56	0.01	T	T,0.0435
24	0.45	5.11	52	0.01	T	T,0.0372
25	0.25	0.6	6	0.16	UD	UD,0.5
26	0.95	3.57	0.129	2.48	HEPD	HEPD,0.25
27	0.07	1	10	1	UD	UD,0.5
28	0.04	1.2	8	0.08	T	T,0.0435
29	0.04	2.2	34	0.04	T	T,0.0446
30	0.02	2.2	24	0.04	T	T,0.0446
31	0.02	10.2	90	0.01	T	T,0.0446
32	0.05	10	118	0.01	T	T,0.0429
33	0.04	1	10	0.1	T	T,0.035
34	0.03	10.8	136	0.007	T	T,0.044
35	0.045	10.2	170	0.009	T	T,0.0435
36	0.041	10.4	108	0.009	T	T,0.0435
37	0.06	1.2	8	0.08	T	T,0.0422
38	1.33	1.09	0.07	3.26	HEPD	HEPD,0.25
39	0.07	2	12	0.05	T	T,0.0417
40	0.05	1.4	6	0.07	T	T,0.0429
41	0.06	2.2	8	0.045	T	T,0.0422
42	0.07	1.6	8	0.062	T	T,0.0417
43	0.07	0.8	10	0.025	UD	UD,0.5
44	0.04	0.2	20	0.5	UD	UD,0.5
45	0.07	1	10	0.1	T	T,0.047
46	1.07	0.506	0.09	3.44	HEPD	HEPD,0.263
47	0.05	17.4	702	0.005	T	T,0.0429
48	0.015	27.2	2210	0.003	T	T,0.0449
49	0.02	22.6	1500	0.004	T	T,0.0446
50	0.04	3.6	32	0.02	T	T,0.0435

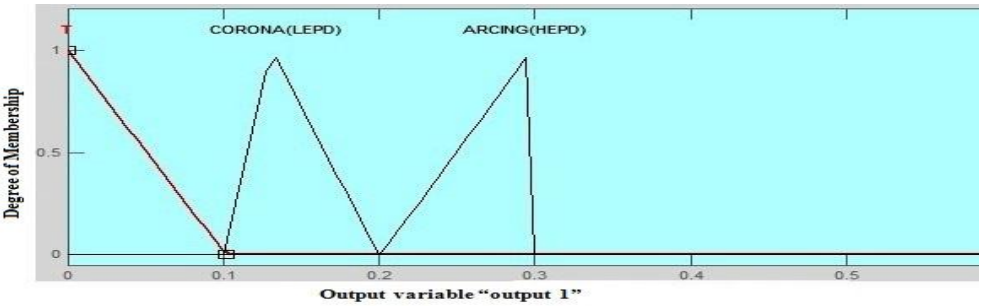

Figure 3. Output MFs for the proposed FL model F1.

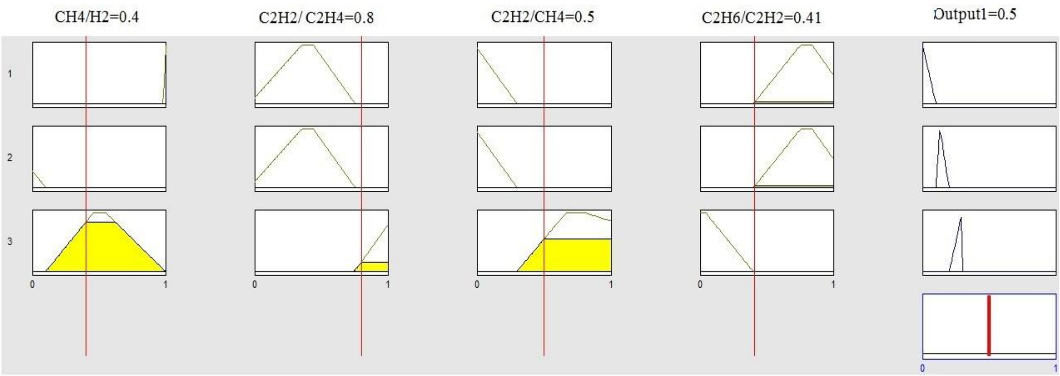

Figure 4. Fuzzy rules for the proposed FL model F1.

For a test sample specified in Table 1, the fault identified by the proposed model is thermal fault. Same fault has been obtained from conventional method. Similarly, the incipient fault obtained from both the methods for all the test samples is given in Table 3, columns 6 and 7.

This method is an advancement of DRM and used in the same way as DRM. RRM can be applied when gas concentration exceeds the specified limit rather than double the specified limit as in DRM [13, 19]. Fault identification in this method is based on gas ratios C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6 and six types of fault (including normal condition) is identified [11, 12]. Faults are detected based on the coding scheme of ratio ranges [14] .A fault is identified when the gas ratios lie in the predetermined ranges as given in below Table 4.

Table 4. Roger's Ratio Codes.

Case	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Fault Type
1	<0.01	<0.1	<1	Normal
2	≥ 1	≥0.1,<0.5	≥1	D1
3	≥0.6, <3	≥0.1,<1	≥2	D2
4	<0.01	≥1	<1	T1
5	<0.1	≥1	≥1,<4	T2
6	<0.2	≥1	≥4	T3

In the present proposed incipient fault model using conventional Roger's Ratio Method, the input membership functions shown in Figure 5 are designed based on the three gas ratios given in Table 4 (columns 2 to 4). Similarly the output membership functions shown in Figure 6 are designed based on column 5 of Table 4. The fuzzy logic expert rules based on input and output MFs are given in Figure 7.

The Proposed Fuzzy Logic Model for Incipient Fault Diagnosis using Roger's Ratio Method (RRM)

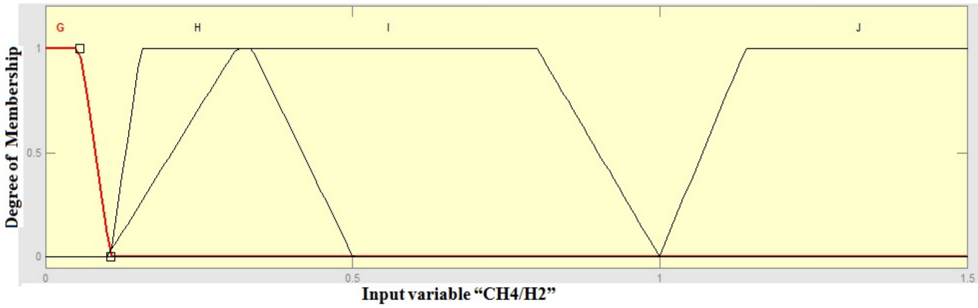

Figure 5. Input MFs for the proposed FL model F2.

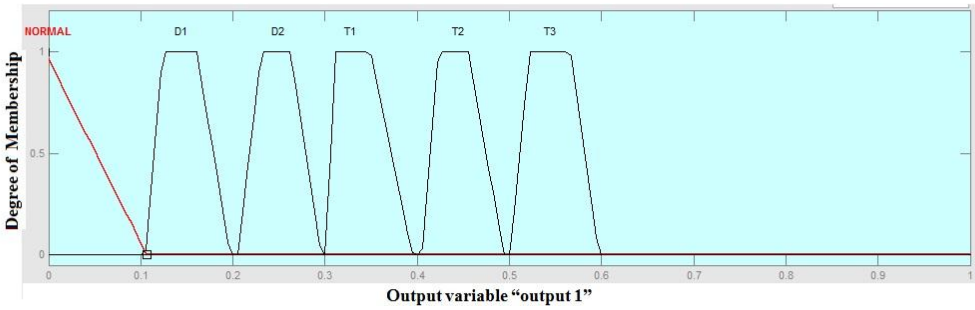

Figure 6. Output MFs for the proposed FL model F2.

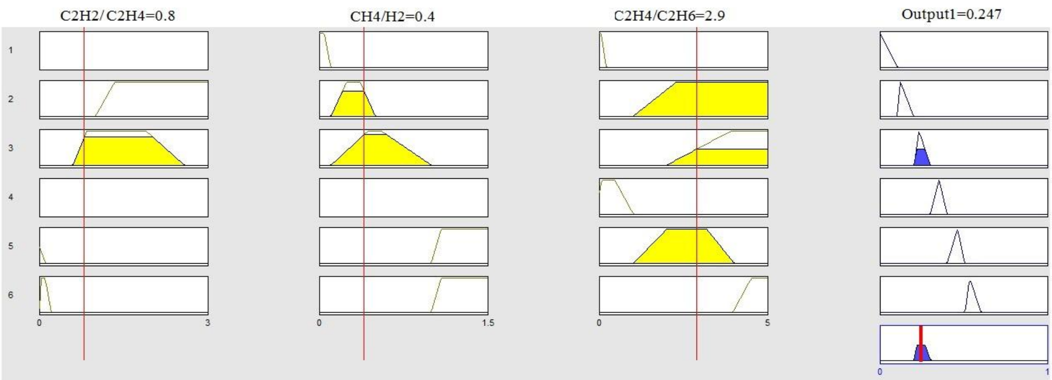

Figure 7. Fuzzy rules for the proposed FL model F2.

For a test sample specified in Table 1, no fault has been identified by the proposed model. Same output has also been obtained from conventional method. Similarly, the incipient fault obtained from both the methods for all the test samples is given in Table 5.

Table 5. Outputs of the conventional Rogers ratio method and the proposed FL model F2

C_2H_2/ C_2H_4	Gas Ratios			Roger's Ratio Method fault identification		Samp le Num ber	Gas Ratios			Roger's Ratio Method fault identification	
	C_2H_2/ C_2H_4	CH_4/ H_2	C_2H_4/ C_2H_6	Conventional Method	Fuzzy Logic Method		C_2H_2/ C_2H_4	CH_4/ H_2	C_2H_4/ C_2H_6	Conventional Method	Fuzzy Logic Method
1	0.0315	5.336	0.119	UD	UD,0.5	26	0.95	3.57	8.12	UD	UD,0.5
2	0.807	0.4627	2.96	D2	D2,0.25	27	0.07	1	1.4	T2	T2,0.45
3	0.666	0.3252	2.428	D2	D2,0.25	28	0.04	1.2	3.25	T2	T2,0.447
4	0.7846	0.3872	2.954	D2	D2,0.25	29	0.04	2.2	0.76	UD	UD,0.5
5	0.0416	1.11	0.104	UD	UD,0.5	30	0.02	2.2	2.5	T2	T2,0.447
6	0.00357	1.45	1.272	T2	T2,0.45	31	0.02	10.2	0.55	UD	UD,0.5
7	0.0243	0.733	0.2928	UD	UD,0.5	32	0.05	10	0.16	UD	UD,0.5
8	0.03	2.739	0.1851	UD	UD,0.5	33	0.04	1	2.6	T2	T2,0.45
9	0.333	0.689	0.2	UD	UD,0.5	34	0.03	10.8	0.22	UD	UD,0.5
10	0.024	24.75	0.051	UD	UD,0.5	35	0.045	10.2	0.12	UD	UD,0.5
11	0.0075	5.12	9.666	T3	T3,0.548	36	0.041	10.4	0.22	UD	UD,0.5
12	0.0283	2.064	4.1046	T3	T3,0.549	37	0.06	1.2	2	T2	T2,0.44
13	1.32	1.62	9.4	UD	UD,0.5	38	1.33	1.09	0.9	UD	UD,0.5
14	0.0295	2	5.98	T3	T3,0.547	39	0.07	2	1.16	T2	T2,0.44
15	0.1739	0.1416	0.7187	UD	UD,0.5	40	0.05	1.4	3	T2	T2,0.44
16	0.04655	1.947	4.748	T3	T3,0.547	41	0.06	2.2	2	T2	T2,0.446
17	0.0036	1.4475	0.6829	T1	T1,0.344	42	0.07	1.6	1.75	T2	T2,0.445
18	0.0032	3.33	1.5	UD	T2,0.45	43	0.07	0.8	1.4	UD	UD,0.5
19	0.00104	0.8125	2.9	UD	UD,0.5	44	0.04	0.2	1.1	UD	UD,0.5
20	0.08	0.972	0.666	UD	UD,0.5	45	0.07	1	1	UD	UD,0.5

21	0.045	8.4	0.28	UD	UD,0.5	46	1.07	0.506	9.96	T2	T2,0.44
22	0.041	5.25	0.42	UD	UD,0.5	47	0.05	17.4	0.02	UD	UD,0.5
23	0.041	6.28	0.42	UD	UD,0.5	48	0.015	27.2	0.029	UD	UD,0.5
24	0.45	5.11	0.42	UD	UD,0.5	49	0.02	22.6	0.028	UD	UD,0.5
25	0.25	0.6	0.66	UD	UD,0.5	50	0.04	3.6	0.75	UD	UD,0.5

5. The proposed Fuzzy Logic Model for Incipient Fault Diagnosis using International Electrotechnical Commission (IEC) Ratio Method

Fault identification in this method is based on gas ratios C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6 (Table 6) but it has different range of ratios as compared to Roger's method and gives better diagnosis result [2,11, 20].

Table 6. IEC ratio codes.

Case	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Fault Type
1	NS	<0.1	<0.2	PD
2	>1	0.1-0.5	>1	D1
3	0.6 -2.5	0.1-1	>2	D2
4	NS	NS	<1	T1
5	<0.1	>1	1-4	T2
6	<0.2	>1	>4	T3
NS - Not significant				

The proposed incipient fault model using IEC Method, the input membership functions shown in Figure 8 are designed based on the three gas ratios given in Table 6 (columns 2 to 4). Similarly the output membership functions shown in Figure 9 are designed based on column 5 of Table 6. The fuzzy logic expert rules based on input and output MFs are given in Figure 10. For a test sample specified in Table 1, no fault has been identified by the conventional IEC method. But, the proposed method determines the fault as thermal fault. Similarly, the incipient fault obtained from both the methods for all the test samples is given in Table 7.

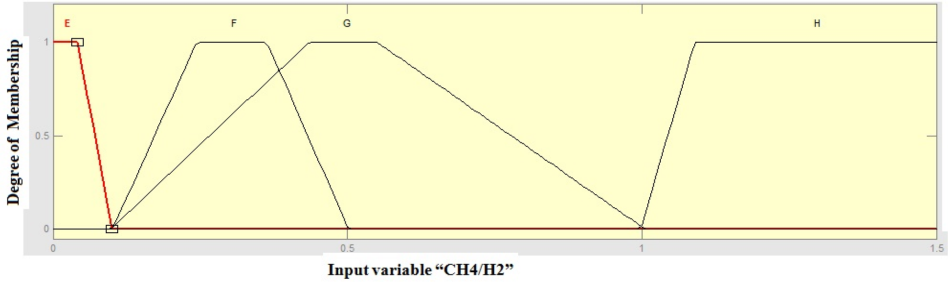

Figure 8. Input MFs for the proposed FL model F3.

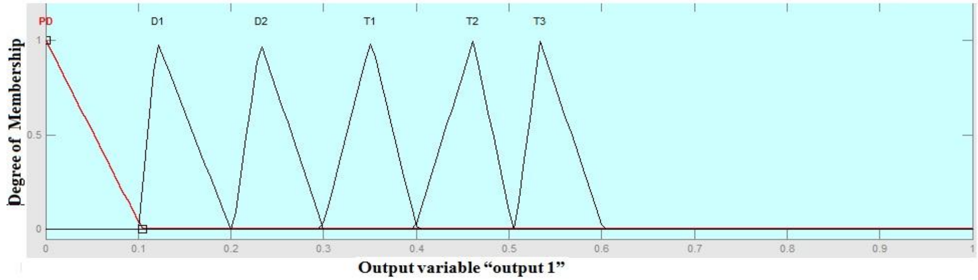

Figure 9. Output MFs for the proposed FL model F3.

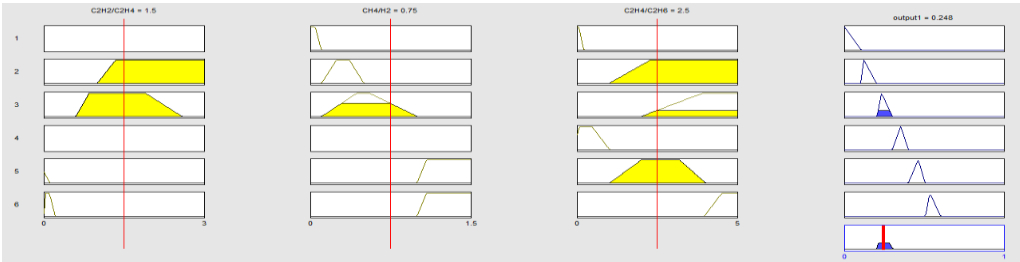

Figure 10. Fuzzy rules for the proposed FL model F3.

Table 7. Outputs of the conventional IEC ratio method and the proposed FL model F3.

Sample Number	Gas Ratios			IEC Ratio Method fault identification		Sample Number	Gas Ratios			IEC Ratio Method fault identification	
	C2H2/ C2H4	CH4/ H2	C2H4/ C2H6	Conventional Method	Fuzzy Logic Method		C2H2/ C2H4	CH4/ H2	C2H4/ C2H6	Conventional Method	Fuzzy Logic Method
1	0.0315	5.336	0.119	T1	T1,0.35	26	0.95	3.57	8.12	UD	0.5
2	0.807	0.4627	2.96	D2	D2,0.247	27	0.07	1	1.4	T2	T2,0.45
3	0.666	0.3252	2.428	D2	D2,0.249	28	0.04	1.2	3.25	T2	T2,0.453
4	0.7846	0.3872	2.954	D2	D2,0.247	29	0.04	2.2	0.76	T1	T1,0.35
5	0.0416	1.11	0.104	T1	T1,0.35	30	0.02	2.2	2.5	T2	T2,0.453
6	0.00357	1.45	1.272	T2	T2,0.45	31	0.02	10.2	0.55	T1	T1,0.35
7	0.0243	0.733	0.2928	T1	T1,0.35	32	0.05	10	0.16	T1	T1,0.35
8	0.03	2.739	0.1851	T1	T1,0.35	33	0.04	1	2.6	T2	T2,0.45
9	0.333	0.689	0.2	T1	T1,0.35	34	0.03	10.8	0.22	T1	T1,0.35
10	0.024	24.75	0.051	T1	T1,0.35	35	0.045	10.2	0.12	T1	T1,0.35
11	0.0075	5.12	9.666	T3	T3,0.55	36	0.041	10.4	0.22	T1	T1,0.35
12	0.0283	2.064	4.1046	T3	T3,0.552	37	0.06	1.2	2	T2	T2,0.452
13	1.32	1.62	9.4	UD	UD,0.5	38	1.33	1.09	0.9	T1	T1,0.349
14	0.0295	2	5.98	T3	T3,0.54	39	0.07	2	1.16	T2	T2,0.45
15	0.1739	0.1416	0.7187	T1	T1,0.35	40	0.05	1.4	3	T2	T2,0.452
16	0.04655	1.947	4.748	T3	T3,0.547	41	0.06	2.2	2	T2	T2,0.452
17	0.0036	1.4475	0.6829	T1	T1,0.35	42	0.07	1.6	1.75	T2	T2,0.45
18	0.0032	3.33	1.5	T2	T2,0.45	43	0.07	0.8	1.4	UD	UD,0.5
19	0.00104	0.8125	2.9	UD	UD,0.5	44	0.04	0.2	1.1	UD	UD,0.5
20	0.08	0.972	0.666	T1	T1,0.35	45	0.07	1	1	T1	T1,0.35
21	0.045	8.4	0.28	T1	T1,0.35	46	1.07	0.506	9.96	D2	D2,0.245
22	0.041	5.25	0.42	T1	T1,0.35	47	0.05	17.4	0.02	T1	T1,0.35
23	0.041	6.28	0.42	T1	T1,0.35	48	0.015	27.2	0.029	T1	T1,0.35
24	0.45	5.11	0.42	T1	T1,0.35	49	0.02	22.6	0.028	T1	T1,0.35
25	0.25	0.6	0.66	T1	T1,0.35	50	0.04	3.6	0.75	T1	T1,0.35

A. Duval Triangle

Duval triangle method is a graphical approach for detecting a fault in oil immersed transformer, was developed by Michel Duval in 1974. In this method percentage concentration of CH_4 , C_2H_2, and C_2H_4 to total three gases are plotted along the sides of the triangle. Triangle is divided into seven fault regions PD: Partial Discharge, T1: Thermal Fault less than 300℃, T2: Thermal Fault between 300 to 700℃, T3:Thermal Fault more than 700℃, D1: Low Energy Discharge (Sparking), D2: High Energy Discharge (Arcing), DT: Mix of Thermal and Electrical Faults [18, 19]. Duval triangle method provides more accurate and consistent diagnosis than other ratio methods. The advantage of this method is that it always provides result with a low percentage of incorrect diagnosis. Fault identification for this method has been done using Duval triangle software and result obtained are tabulated below Table 8.

Table 8. Identified fault using Duval triangle method

Sample Number	Gas contents (ppm)			Percentage (%) Gas concentration			Identified Fault
	CH4	C2H4	C2H2	%CH4	%C2H4	%C2H2	
1	103	19	0.6	84	15.5	0.5	T1
2	230	151	122	45.7	30	24.3	D2
3	200	102	68	54.1	27.6	18.4	D2
4	230	130	102	49.8	28.1	22.1	D2
5	30	2.4	0.1	92.3	7.4	0.3	T1
6	55	28	0.1	66.2	33.7	0.1	T2
7	22	4.1	0.1	84	15.6	0.4	T1
8	63	10	0.3	85.9	13.6	0.5	T1
9	2	0.3	0.1	83.3	12.5	4.1	DT
10	99	4.2	0.1	95	4.1	0.1	T1
11	286	928	7	23.4	76	0.6	T3
12	161	353	10	30.7	67.4	1.9	T3
13	34	47	62	25.5	35.3	46.6	D2
14	100	305	9	24.1	73.6	2.1	T3
15	17	23	4	38.6	52.3	9.1	D1
16	335	812	37.8	28.3	68.5	3.2	T3
17	262	28	0.1	90.31	9.6	0.03	T1
18	90	63	0.2	58.7	41.1	0.13	T2
19	130	96	0.1	57.4	42.4	0.04	T2
20	175	50	4	76.4	21.8	1.7	T2
21	42	11	<0.5	78.5	20.6	0.9	T2
22	42	12	<0.5	77.06	22.01	0.91	T2
23	44	12	<0.5	77.8	21.23	0.88	T2
24	46	11	<0.5	80	19.13	0.86	T1
25	3	2	<0.5	90	36	9	DT
26	25	65	62	16.44	42.76	40.78	D2

27	5	7	<0.5	40	56	4	T3
28	6	13	<0.5	30.76	66.66	2.5	T3
29	11	13	<0.5	44.8	53.06	2	T3
30	11	30	<0.5	26.5	72.28	0.012	T3
31	51	25	<0.5	66.66	32.67	0.65	T2
32	50	10	<0.5	82.64	16.52	0.82	T1
33	5	13	<0.5	27.02	70.27	2.7	T3
34	65	15	<0.5	80.74	18.63	0.621	T1
35	51	11	<0.5	81.6	17.6	0.8	T1
36	52	12	<0.5	0.806	0.186	0.775	T1
37	6	8	<0.5	41.37	55.17	3.4	T3
38	45	110	147	14.9	36.42	48.67	D2
39	10	7	<0.5	57.14	40	2.85	T2
40	7	9	<0.5	42.4	54.5	3	T3
41	11	8	<0.5	56.4	41	2.56	T2
42	8	7	<0.5	51.6	45.16	3.22	T2
43	4	7	<0.5	34.78	60.86	4.34	T3
44	<1	11	<0.5	8	88	4	T3
45	5	7	<0.5	40	56	4	T3
46	256	817	881	13.1	41.81	45.08	D2
47	87	10	<0.5	89.23	10.25	0.513	T1
48	136	33	<0.5	80.23	19.46	0.294	T1
49	113	21	<0.5	84.01	15.61	0.37	T1
50	18	12	<0.5	59.01	39.34	1.63	T2

6. The Proposed Expert System Fuzzy Logic Model for Incipient Fault Diagnosis

In present section, fuzzy logic sub-models presented above have been joined in a overall incipient fault model shown in Figure 11. It uses all conventional DGA interpretation methods, and provides type of incipient fault present in transformers as output. The output MFs of every individual sub-model are considered as input MFs for the overall incipient fault model. The output MFs for the proposed overall incipient fault model are given in Figures 12. All possible combinations formed between input and output MFs are considered in fuzzy rules for the proposed model, and are shown in Figure 13.

Similarly, the output obtained from this model for all the test samples is given in Table 9. It has been observed that the proposed model determines the type of incipient fault for all the test samples whereas the conventional DGA interpretation methods fail to identify them for some of the test samples numbered 7, 9, 13, 15, 26, 38, 43 and 44 (Table 9). In case of sample number 15, conventional methods failed to determine type of fault (UD i.e. undetermined). But from Table 6, it has been observed that the concentrations of dissolved gasses exceed their permissible limits [17]. It represents the existence of fault. However, the proposed model determines the type of incipient fault as D1 (i.e. low temperature thermal fault). Similar observations were found in case of test samples 7, 9, 13, 26, 38, 43 and 44. Thus the proposed model overcomes the shortcomings of all the conventional DGA interpretation methods. Also the severity of the fault is calculated by the proposed model whereas the conventional methods only identify the type of fault.

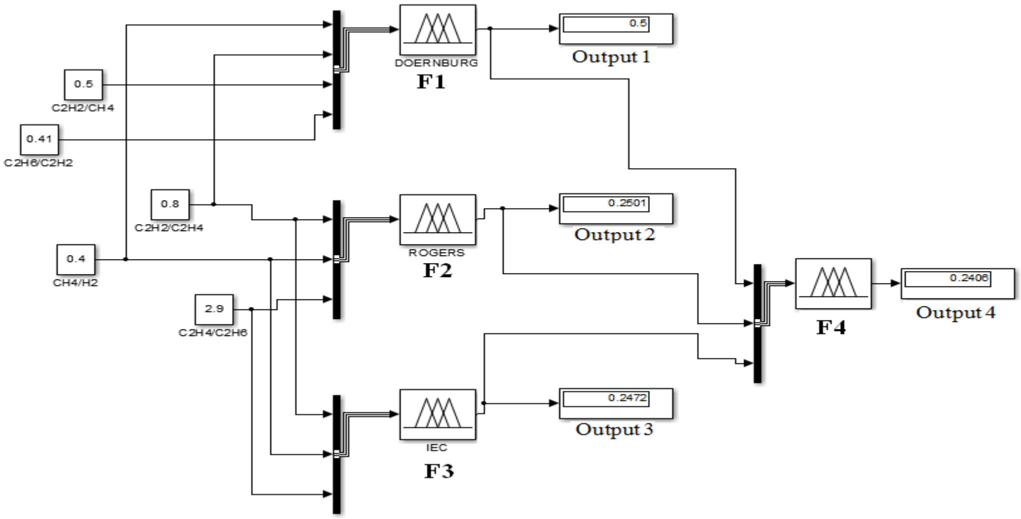

Figure 11. The proposed expert system for incipient fault diagnosis of transformers.

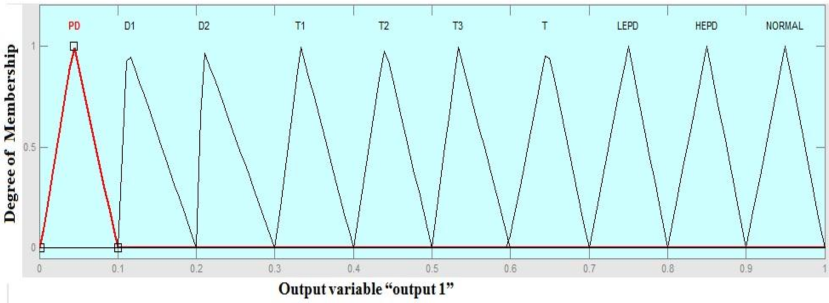

Figure 12. Output MFs for the proposed FL model F4.

Figure 13. Fuzzy rules for the proposed FL model F4.

Table 9. Output of the proposed FL model F4.

Sample Number	C_2H_2/ C_2H_4	CH_4/ H_2	C_2H_4/ C_2H_6	C_2H_2/ CH_4	C_2H_6/ C_2H_2	Expert System 3 Methods	Identified Fault using Duval Triangle Method
1	0.0315	5.336	0.119	0.005	265	T1,0.344	T1
2	0.807	0.4627	2.96	0.5	0.41	D2,0.241	D2
3	0.666	0.3252	2.428	0.34	0.61	D2,0.241	D2
4	0.7846	0.3872	2.954	0.4	0.43	D2,0.241	D2
5	0.0416	1.11	0.104	0.003	230	T1,0.345	T1
6	0.00357	1.45	1.272	0.001	220	T2,0.447	T2
7	0.0243	0.733	0.2928	0.004	140	UD,0.5	T1
8	0.03	2.739	0.1851	0.004	180	T1,0.344	T1
9	0.333	0.689	0.2	0.05	15	UD,0.5	DT
10	0.024	24.75	0.051	0.001	820	T1,0.344	T1
11	0.0075	5.12	9.666	0.02	13.7	T3,0.545	T3
12	0.0283	2.064	4.1046	0.06	8.6	T3,0.545	T3
13	1.32	1.62	9.4	1.8	0.08	HEPD,0.85	D2
14	0.0295	2	5.98	0.09	5.66	T3,0.545	T3
15	0.1739	0.1416	0.7187	0.23	8	UD,0.5	D1
16	0.04655	1.947	4.748	0.11	4.52	T3,0.545	T3
17	0.0036	1.4475	0.6829	0.003	410	T1,0.344	T1
18	0.0032	3.33	1.5	0.003	210	T2,0.447	T2
19	0.00104	0.8125	2.9	0.0007	330	T2,0.5	T2
20	0.08	0.972	0.666	0.02	18.75	T2,0.5	T2
21	0.045	8.4	0.28	0.01	76	T2,0.344	T2
22	0.041	5.25	0.42	0.01	56	T2,0.344	T2
23	0.041	6.28	0.42	0.01	56	T1,0.344	T1
24	0.45	5.11	0.42	0.01	52	T1,0.345	T1
25	0.25	0.6	0.66	0.16	6	DT,0.5	DT
26	0.95	3.57	8.12	2.48	0.129	HEPD,0.85	D2
27	0.07	1	1.4	1	10	T3,0.447	T3
28	0.04	1.2	3.25	0.08	8	T3,0.447	T3
29	0.04	2.2	0.76	0.04	34	T1,0.344	T1
30	0.02	2.2	2.5	0.04	24	T2,0.447	T2
31	0.02	10.2	0.55	0.01	90	T1,0.344	T1
32	0.05	10	0.16	0.01	118	T1,0.345	T1
33	0.04	1	2.6	0.1	10	T2,0.447	T3
34	0.03	10.8	0.22	0.007	136	T1,0.344	T1
35	0.045	10.2	0.12	0.009	170	T1,0.344	T1

36	0.041	10.4	0.22	0.009	108	T1,0.344	T1
37	0.06	1.2	2	0.08	8	T2,0.447	T2
38	1.33	1.09	0.9	3.26	0.07	HEPD,0.85	D2
39	0.07	2	1.16	0.05	12	T2,0.447	T2
40	0.05	1.4	3	0.07	6	T3,0.447	T3
41	0.06	2.2	2	0.045	8	T2,0.447	T2
42	0.07	1.6	1.75	0.062	8	T2,0.447	T2
43	0.07	0.8	1.4	0.025	10	UD,0.5	T3
44	0.04	0.2	1.1	0.5	20	UD,0.5	T3
45	0.07	1	1	0.1	10	T1,0.344	T1
46	1.07	0.506	9.96	3.44	0.09	D2,0.251	D2
47	0.05	17.4	0.02	0.005	702	T1,0.345	T1
48	0.015	27.2	0.029	0.003	2210	T1,0.344	T1
49	0.02	22.6	0.028	0.004	1500	T1,0.344	T1
50	0.04	3.6	0.75	0.02	32	T1,0.344	T2

Thus the FL models proposed in the present work effectively computes type of incipient fault present in transformers. These models can also determine faults correspond to multiple faults case along with their severity.

7. Conclusion

The paper presents proposes a novel FL model to evaluate the various incipient faults of transformer. It integrates the results of Dissolved gas analysis. The method determines the incipient fault by using the information obtained from Doernenburg, Rogers and IEC ratio code methods. Further, it also determines the severity of fault. It has been found from the outcomes of the present work that the proposed models are reliable and accurate as compared to conventional fault diagnosis methods. These models also overcome the various difficulties of conventional methods in identifying the multiple faults. Fifty different transformer oil samples collected from Himachal Pradesh State Electricity Board, Shimla were used to evaluate the efficiency of the proposed FL models. It is envisioned that the proposed models are convenient and accurate. Also these models are easy to implement for utility mangers as well as customers. This shall help to initiate preventive maintenance actions timely so that a huge loss can be avoided.

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Zakir Husain received his Bachelor and Master degrees in Electrical Engineering from Aligarh Muslim University, Aligarh, India. Subsequently he obtained his Ph.D from Motilal Nehru National Institute of Technology, Allahabad, India. He has been employed as Lecturer in Department of Electrical Engineering, National Institute of Technology, Hamirpur (H.P.), India since 1989. During 2011 and 2012 he was on Academic pursuit and worked as Head, Department of Electrical Engineering, College of Engineering, Salman Bin Abdulaziz University, Kingdom of Saudi Arabia. Presently, he is working as Head of Electrical Engineering Department, NIT Hamirpur. His principal research interests are Multi Phase Power Systems, Electric Drives, Condition Monitoring of Electric Equipment, and Renewable Energy Resources. He is the Counselor of IEEE student branch, NIT Hamirpur.