Determination of Partial Discharge Severity in Power Transformers Based on the Starting Decomposing Material

Sherif S.M. Ghoneim
Faculty of Industrial Education,
Suez University , Egypt
sherif.ghoneam@suezuniv.edu.eg

Sobhy. S. Dessouky
Faculty of Engineering,
Port Said University , Egypt
sobhyserry@yahoo.com

Adel A. Elfaraskoury
Laboratories& Researches and Tests,
Egyptian Electricity Holding Company
Cairo, Egypt
dr.adel_elfaraskoury@yahoo.com

Ramy. N. R. Ghaly
Mataria Technical College in Cairo
Ministry of Higher Education
Cairo, Egypt
ramyelectric@yahoo.com

Abstract— **Dissolved gas analysis (DGA) is a common technique to identify the transformer faults. The transformer faults are identified based on the concentration of the combustible gases such as Hydrogen (H_2), Methane (CH_4), Ethan (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), and Carbon mono-oxide (CO) in addition to the ratios between these gases. On the other hand, the DGA technique identifies only the transformer fault type not the severity of this fault. In this paper, three objectives should be achieved, the first one is determining the transformer fault type based on the Duval triangle rules using a Fuzzy Logic model and secondly, determining the partial discharge severity based on a thermodynamic approach based on the starting decomposing materials (n-Octane (C_8H_{18}) and Eicosane ($C_{20}H_{42}$)), thirdly, comparing the severity of the partial discharge based on the type of the starting decomposing material. The results indicate that the severity of the partial discharge influenced by the type of starting decomposing material.**

Keywords—Partial discharge, power transformer, dissolved gas analysis, insulating oil.

I. INTRODUCTION

A power transformer is one of the most important parts in the power network so its reliable operation is necessary. Early stage detection of transformer faults avoided a catastrophic damage and unwanted outage of the transformer from the network [1]. Most of the transformer faults were developed in the insulation systems, which consists of the insulating oil and paper. Due to electrical, thermal and mechanical stresses, the insulation oils degraded and decomposed. The decomposing of the insulation oil generated dissolved gases, which were categorized to combustible and incombustible gases. These gases are Hydrogen (H_2), Methane (CH_4), Ethan (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), and Carbon mono-oxide (CO). These Hydrocarbon gases are combustible gases and the energy required to form these gases increases in the order $CH_4 < C_2H_6 <= CO <= C_2H_4 <= H_2 << C_2H_2$. There were several DGA techniques, such as Dornenburg method, Rogers' method, Key gas method, Interational Electro-technical Commission (IEC) standard code, and graphical representation method (triangle and pentagon), which were used to diagnose the transformer faults [1-4]. Recently, artificial intelligent techniques are merged with the previous DGA techniques to enhance the diagnostic accuracy [1, 5-13]. In spite of the ability of DGA techniques to detect the transformer faults, they can't monitor the severity of these faults [14].

The conventional DGA techniques such as Dornenburg ratio method, Rogers ratio method and IEC standard code were based on the ratios between main five combustible gases such as Hydrogen (H_2), Methane (CH_4), Ethan (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2). For Dornenburg ratio method, the ratios are CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2. For Rogers four ratio method, the ratios are CH_4/H_2, C_2H_2/C_2H_4, C_2H_4/C_2H_6 and C_2H_6/CH_4. For IEC Standard code, the ratios were CH_4/H_2, C_2H_2/C_2H_4 and C_2H_4/ C_2H_6. The previous methods have poor accuracy for detecting transformer faults and in some conditions, it fails to interpret the transformer fault type. The Duval triangle is one of the conventional DGA methods and it is stable and reliable for many years and its common population DGA method all over the world. It depends on percentage of three combustible gases only which are Methane (CH_4), Ethylene (C_2H_4), Acetylene (C_2H_2) to their sum. All of these conventional methods were addressed in detail in [1].

The total dissolved combustible gases (TDCG) were used as an indication of the severity of the transformer conditions accordingly the maintenance actions are addressed [2, 15]. The TDCG which is the sum of all combustible gases is not sufficient to determine the fault severity since it did not take into account which gas rate was varied. The impact of the energy weighted of the dissolved gases was addressed in [16] that to evaluate the severity of transformer faults. The proposed Artificial Neural Network (ANN) model based on the rules of Duval triangle was built to identify the transformer fault and used n-octane as a starting decomposing material to determine the transformer fault severity [3]. On the other hand, Eicosane was used as a starting decomposing material to investigate the severity of the transformer fault [17]. The diagnostic fault model was constructed based on the rules of IEC standard code.

An Eicosane and n-octane were two starting decomposing material, which were used in the thermodynamic approach to estimate the severity of the transformer fault [14-17]. In this paper, the impact of the starting decamping material (Eicosane and n-octane) to determine the partial discharge severity was addressed. This comparative study was an evidence to explain that the variation of the starting decomposing materials led to a variation of the partial discharge fault severity. The constructed model to identify the partial discharge fault severity was based on the Duval triangle method, where the fault type was determined using a fuzzy logic system based on Duval triangle fault region rules. The results are based on random selected samples demonstrated that the partial discharge severity is medium with Eicosane and low severity with n-octane. For the emergency condition, the maintenance process should take into consideration the results based on Eicosane.

II. DGA BASED ON THE DUVAL TRIANGLE METHOD

The Duval triangle is a common DGA method for transformer fault diagnosis and was built using more than 1000 DGA samples of faulted transformers. Diagnosis of the transformer fault was based on the relative ratio of three combustible gases (CH_4, C_2H_4, and C_2H_2) referred to the sum of the three gases [2, 3, 18]. Figure 1 shows the fault zones and the corresponding boundary based on the percentage of (CH_4, C_2H_4, and C_2H_2) and Table 1 demonstrated the meaning of each abbreviation. The gases' percentage can be calculated as follows;

$$[X_{DT}] = [\%CH_4, \%C_2H_4, \%C_2H_2]^T \quad (1)$$

Where,

$$\%CH_4 = \frac{CH_4}{C_2H_2+C_2H_4+CH_4} \times 100$$

$$\%C_2H_4 = \frac{C_2H_4}{C_2H_2+C_2H_4+CH_4} \times 100$$

$$\%C_2H_2 = \frac{C_2H_2}{C_2H_2+C_2H_4+CH_4} \times 100$$

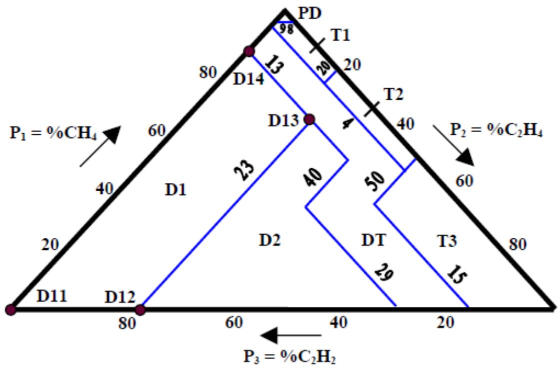


Fig. 1. Duval triangle as a diagnostic tool to detect incipient faults in transformers [19]

TABLE 1 Legend of Duval triangle

Legend
PD=Partial Discharge
T1=Thermal fault less than 300ºC
T2=Thermal fault between 300 ºC and 700 ºC
T3=Thermal fault greater than 700 ºC
D1=Low energy discharge (sparking)
D2=High energy Discharge (Arcing)
DT=Mix of thermal and electrical fault

III. THE FUZZY LOGIC SYSTEM BASED ON THE DUVAL TRIANGLE METHOD

The inputs of the Duval triangle fuzzy system were CH_4%, C_2H_4%, and C_2H_2%, the outputs were constant referring to the fault type (FT), and the rules box was as Sugeno. A trapezoidal membership function was selected to express the system inputs and every input was categorized to ten membership functions (mf1-mf10). The membership function boundaries for all inputs were indicated in Table 2.

TABLE 2: the boundaries of the membership functions of each input variable

CH_4%		**C_2H_4%**		**C_2H_2%**	
mf	limits	mf	limits	mf	limits
1	[-0.05 0 86 86]	1	[-0.05 0 23 23]	1	[12.99 13 99.99 100]
2	[-0.05 0 64 64]	2	[22.99 23 40 40]	2	[13 13 99.99 100]
3	[-0.05 0 30.99 31]	3	[39.99 40 70.99 71]	3	[29 29 70.99 71]
4	[98 98 100 100]	4	[-0.05 0 1.999 2]	4	[-0.05 0 1.999 2]
5	[76 76 97.99 98]	5	[-0.05 0 20 20]	5	[-0.05 0 3.999 4]
6	[45.99 46 80 80]	6	[20 20 50 50]	6	[-0.05 0 3.999 4]
7	[-0.05 0 50 50]	7	[50 50 100 100]	7	[-0.05 0 15 15]
8	[47 47 96 96]	8	[-0.05 0 40 40]	8	[3.99 4 13 13]
9	[27 27 50 50]	9	[40 40 50 50]	9	[3.99 4 29 29]
10	[-0.05 0 35 35]	10	[50 50 100 100]	10	[14.99 15 29 29]

Seven membership functions expressed the output, which were selected as a constant membership function. Each one of the transformer fault types can be expressed using a number from 1 to 7, where, 1 for PD, 2 for D1, 3 for D2, 4 for T1, 5 for T2, 6 for T3 and 7 for Undermined fault (UD). The rules of the constructed fuzzy system can be shown as in Fig. 2. This Figure demonstrated the relation between the inputs and the output of the system, i.e., when the CH_4% was 99.9999%, C_2H_4% was 0.000014%, and C_2H_2% was 0.000014%, then the output was "1" which referred to the partial discharge fault (PD). In addition, Fig. 3 explained the SIMULINK model of the constructed system.

IV. THERMODYNAMIC MODEL

(A) N-OCTANE (C_8H_{18}) STARTING DECOMPOSING MATERIALS

An n-octane was selected as starting decomposing compound in the thermodynamic approach to investigate the severity of transformer faults. It is a paraffin compound that generates gases when the insulating oil subjects to stresses (thermal or electrical). The following equations demonstrate the decomposing of n-octane to the gases that produced during stresses on the transformer oil such as H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 [14-15];

$$C_8H_{18}(l)=CH_4(g)+C_7H_{14}(l) \quad (2.a)$$

$$C_8H_{18}(l)=C_2H_6(g)+C_6H_{12}(l) \quad (2.b)$$

$$C_8H_{18}(l)=C_2H_4(g)+C_6H_{14}(l) \quad (2.c)$$

$$C_8H_{18}(l)=H_2(g)+C_8H_{16}(l) \quad (2.d)$$

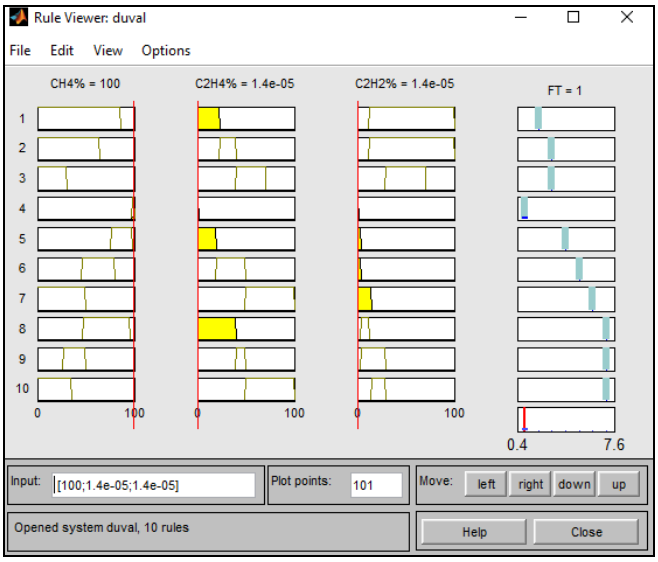
$$C_8H_{18}(l)=C_2H_2(g)+H_2(g)+C_6H_{14}(l) \quad (2.e)$$

where, “g” refers to gas state and “l” refers to liquid state.

The thermodynamic model based in n-octane can be illustrated as follows;

- The hydrocarbon decomposing is an endothermic reaction, and then absorbs energy from the surroundings.
- The enthalpy change expresses the heat content of each reaction.

The enthalpy of reaction ($\Delta H_{reaction}$) is the difference between the enthalpy of the formation of the products $(\Delta H^o_f)_p$ and the enthalpy of the formation of the reactants $(\Delta H_f)_R$ which refers to the enthalpy of formation of the fault gases.



Input: [100;1.4e-05;1.4e-05]

Plot points: 101

Opened system duval, 10 rules

Fig. 2. The diagram illustrated the rules of the constructed fuzzy system

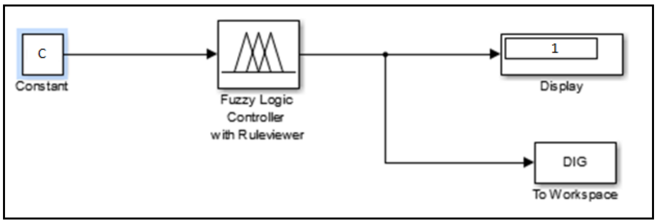


Fig. 3. The SIMULINK model of the proposed algorithm

After computing the reaction of formation of the fault gases, the energy weighted factor can be determined by taking the enthalpy of reaction of Methane (CH_4) as a reference as follows;

The enthalpy change of reaction can be calculated as (3);

$$\Delta H^o_{reaction}=\Delta H^o_{f,\,products}-\Delta H^o_{f,\,reactants} \quad (3)$$

where, (ΔH^o_f) is the enthalpy of formation, therefore, a sample calculation of the $(\Delta H^o_{reaction})$ for reaction (2.a) is as follows;

$$\Delta H^o_{f,\,products}=\Delta H^o_f\,(CH_4)+\Delta H^o_f\,(C_7H_{14}) \quad (4)$$

The standard enthalpies of the formation CH_4 and C_7H_{14} were shown as in Table 3 and were substituted in (4).

Hence,

$$\Delta H^o_{f,products} = -74.9-97.7=-172.6\ kJ/mol \quad (5)$$

The standard enthalpy of the reactants is estimated by,

$$\Delta H^o_{f,reactants} = \Delta H^o_f\,(C_8H_{18}) = -250.3\,\frac{kJ}{mol} \quad (6)$$

Therefore, the enthalpy change of reaction $(\Delta H^o_{reaction})$ for CH_4 can be calculated based on (3) by,

$$\Delta H^o_{reaction}\ (CH_4) = \Delta H^o_{f,products} - \Delta H^o_{f,reactants} = -172.6—(-250.3) = 77.7\ kJ/mol \quad (7)$$

TABLE 3 Enthalpy of formation for each product of n-octane (C8H18) decomposing reactions at 298oK and 105 KPA [15]

molecule	**ΔH^o_f**	**molecule**	**ΔH^o_f**
$C_8H_{18}\,(l)$	-250.3	$CH_4(g)$	-74.9
$C_7H_{14}\,(l)$	-97.7	$C_2H_6(g)$	-83.8
$C_6H_{14}\,(l)$	-198.7	$C_2H_4(g)$	52.5
$C_6H_{12}\,(l)$	-73	$C_2H_2(g)$	226.7
$C_8H_{16}\,(l)$	-121.8	$H_2(g)$	0

By the same manner, the other n-octane product gases can be computed as in Table 4 based on the enthalpy change of the formation for each gas and liquid product as in Table 3. Therefore, the relative energy factor (*REF*) for each gas can be calculated as in Table 4;

The energy weighted based on the five gases (H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2) for the n-octane gas product can be calculated as in (8);

$$Energy\ weighted(\,HMEEA\,)=C(\,CH_4\,)\times REF_1+C(\,C_2H_6\,)\times REF_2 +C(\,C_2H_4\,)\times REF_3+C(\,H_2\,)\times REF_4+C(\,C_2H_2\,)\times REF_5 \quad (8)$$

The abbreviation (*HMEEA*) refers to Hydrogen, Methane, Ethan, ethylene, and Acetylene.

TABLE 4 Enthalpy of reaction for each gas that was produced from n-octane decomposing [14-15]

Product gas	**$(\Delta H^o_f)_{\text{Reactants}}$**	**$(\Delta H^o_f)_{\text{Products}}$**	**$(\Delta H^o_{reaction})$ as in (5)**	***REF***	
CH_4	-250.3	-172.6	77.7	*REF1*	77.7/77.7=1.00
C_2H_6	-250.3	-156.8	93.5	*REF2*	93.5/77.7=1.20
C_2H_4	-250.3	-146.2	104.1	*REF3*	104.1/77.7=1.34
H_2	-250.3	-121.8	128.5	*REF4*	128.5/77.7=1.65
C_2H_2	-250.۳	28.0	278.3	*REF5*	278.3/77.7=3.58

(B) EICOSANE ($C_{20}H_{42}$) STARTING DECOMPOSING MATERIAL

A n-octane consists of paraffin molecules which were not stable and removed from the crude oil during its production process and hence, the energy required for cracking reaction to generate n-octane can be neglected. Due to n-octane kept in the fault zone for a long time to achieve the equilibrium state, therefore, it considered a great issue [15]. Hence, the Eicosane ($C_{20}H_{42}$) was proposed to construct the thermodynamic model to identify the severity of the transformer faults based on DGA. Equations 9a to 9b, demonstrate the reaction to produce the combustible gases that was used in the thermodynamic approach as follows [17];

$$C_{20}H_{42}(l) = CH_4(g) + C_{19}H_{38}(l) \tag{9.a}$$

$$C_{20}H_{42}(l) = C_2H_6(g) + C_{18}H_{36}(l) \tag{9.b}$$

$$C_{20}H_{42}(l) = C_2H_4(g) + C_{18}H_{38}(l) \tag{9.c}$$

$$C_{20}H_{42}(l) = H_2(g) + C_{20}H_{40}(l) \tag{9.d}$$

$$C_{20}H_{42}(l) = C_2H_2(g) + H_2(g) + C_{18}H_{38}(l) \tag{9.e}$$

Table 5 shows the enthalpy change of formation of each product of the Eicosane ($C_{20}H_{42}$). Based on the magnitude of the enthalpy change of formation of each Eicosane product as in Table 5, the enthalpy change of the reaction of the gas product can be calculated as in Table 6. In order to calculate the energy weighted required to develop the gas product from Eicosane equation (8) was applied.

TABLE 5 Enthalpy of formation for each product of Eicosane (C20H42) decomposing reactions at 298oK and 105 KPA [17]

molecule	***ΔH^o_f***	***molecule***	***ΔH^o_f***
$C_{20}H_{42}$ (l)	-455.8	CH_4(g)	-74.9
$C_{20}H_{40}$ (l)	-357.9	C_2H_6(g)	-83.8
$C_{19}H_{38}$ (l)	-345.9	C_2H_4(g)	52.5
$C_{18}H_{38}$ (l)	-414.6	C_2H_2(g)	226.7
$C_{18}H_{36}$ (l)	-314.1	H_2(g)	0

TABLE 6 Enthalpy of reaction for each gas that was produced from Eicosane decomposing [17]

Product gas	**$(\Delta H^o_f)_{Reactants}$**	**$(\Delta H^o_f)_{Products}$**	**$(\Delta H^o_{reaction})$ as in (5)**	***REF***	
CH_4	-455.8	-420.8	35	*REF1*	35/35=1
C_2H_6	-455.8	-397.9	57.9	*REF2*	57.9/35=1.65
C_2H_4	-455.8	-362.1	93.7	*REF3*	93.7/35=2.68
H_2	-455.8	-357.9	97.9	*REF4*	97.9/35=2.8
C_2H_2	-455.8	-187.9	267.9	*REF5*	267.9/35=7.65

V. SEVERITY OF THE PARTIAL DISCHARGE

The severity of the partial discharge is investigated based on the variation of the starting decomposing material (n-octane and Eicosane). The magnitude of partial discharge is not sufficient to assess the life expectancy of the insulation. Hence, additional information was required to estimate the severity of the partial discharge. This information is the energy that was associated with the decomposing process of the insulating oils due to different stresses like electrical, thermal, and mechanical stresses. Based on equation (8), the energy weighted of the main five gases (H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2) can be calculated for n-octane and Eicosane and then the relative ratio between the energy weighted of the five gases and its total concentration can be computed as follows;

EWRO=Energy weighted HMEEA for n-octane/HMEEA concentration (10)

Where, *EWRO* refers to the Energy weighted ratio of n-octane.

EWRE=Energy weighted HMEEA for Eicosane/HMEEA concentration (11)

Where, *EWRE* refers to the Energy weighted ratio for Eicosane.

According to the equations (10) and (11), the energy weighted ratios for n-octane and Eicosane (EWRO and EWRE) were computed. The magnitude of the EWRO and EWRE ranged from 0 to 8. The low PD severity was considered when EWRO and EWRE were less than or equal 2, moderate when EWRO and EWRE were greater than 2 and less than or equal 4 and the severity was high when EWRO and EWRE were greater than 4 [14].

Although the rules for detecting the transformer fault using Duval triangle DGA technique were based on only three gases (CH_4, C_2H_4, and C_2H_2), the accuracy of the Duval triangle to detect partial discharge fault is poor. This fact is due to the importance of H_2 concentration in partial discharge fault detection. Hence, the concentration of H_2 as well as C_2H_6 was taken into account for computing the energy weighting ratio with three other gases for the Duval triangle method. The relative energy factor (*REF*) for each gas based on the starting decomposing material was explained in Tables 4 and 6.

Table 7 explains the cases under considerations and contains 15th columns, column 1 refers to the case number, and the next five columns indicated the concentration of H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 in ppm. The *ACT* column expresses the actual fault of each case and "1" refers to a partial discharge fault and "4" to the low thermal fault. The eighth, ninth, and tenth columns explained the percentage of CH_4, C_2H_4 and C_2H_2 referred to the sum of them as in (1). Eleventh and twelfth columns refer to the energy weighted ration for n-octane and Eicosane (*EWRO* and *EWRE*) respectively. The *DIG* column indicates the Duval triangle method diagnosis, which agrees with the actual fault of all samples referring to the accuracy of Duval triangle for detecting the fault type (100%). The last two columns (*SEV_E* and *SEV_O*) illustrate the severity of the partial discharge fault based on the magnitude of *EWRE* and *EWRO*. When the severity using n-octane and Eicosane is 1, it refers to low severity and when it is 2, it refers to medium severity, on the other hand, 3 refers to high fault severity.

The severity based on EWRO and EWRE is different for all studied cases As in case number 7, when the CH_4% was 99.99996%, C_2H_4% was 0.000004%, and C_2H_2% was 0.000004%, and then the output was "1" which referred to the partial discharge fault (PD), and the severity based on EWRE (SEV_E) refers to 2 (medium severity) and the severity based on EWRO (SEV_O) refers to 1 (low severity). Therefore, based on the results of Table 7 the decomposing starting material has a significant effect in determining the severity of the partial discharge fault. For emergency monitoring of the fault severity based on the starting decomposing material, the severity results based Eicosane must be taken into consideration rather than that based on n-octane.

TABLE 7 The cases to investigate the severity based on the starting decomposing material

Case	*H_2*	*CH_4*	*C_2H_6*	*C_2H_4*	*C_2H_2*	*ACT*	*CH_4%*	*C_2H_4%*	*C_2H_2%*	*EWRE*	*EWRO*	*DIG*	*SEV_E*	*SEV_O*
1	110	7	<0.01	<0.01	<0.01	1	100	0.000014	0.000014	2.65	1.61	1	2	1
2	134	13	156	<0.01	<0.01	1	100	0.000008	0.000008	2.10	1.39	1	2	1
3	1458	9	1812	<0.01	<0.01	1	100	0.000011	0.000011	2.13	1.4	1	2	1
4	195	5.3	<0.01	<0.01	<0.01	1	100	0.000019	0.000019	2.71	1.63	1	2	1
5	109	16	<0.01	<0.01	<0.01	1	100	0.000006	0.000006	2.53	1.57	1	2	1
6	100	18	<0.01	<0.01	<0.01	1	100	0.000006	0.000006	2.49	1.55	1	2	1
7	160	24.7	38.5	<0.01	<0.01	1	100	0.000004	0.000004	2.37	1.50	1	2	1
8	187	5	1	<0.01	<0.01	1	100	0.00002	0.00002	2.7	1.63	1	2	1
9	121	3	1	<0.01	<0.01	1	100	0.000033	0.000033	2.7	1.63	1	2	1
10	32930	2397	157	<0.01	<0.01	1	100	0	0	2.64	1.60	1	2	1
11	37800	1740	249	8	8	1	99.1	0.455581	0.455581	2.68	1.62	1	2	1
12	8266	1061	22	<0.01	<0.01	1	100	0	0	2.56	1.58	1	2	1
13	9340	995	60	6	7	1	98.7	0.595238	0.694444	2.59	1.59	1	2	1
14	36036	4704	554	5	10	1	99.7	0.105955	0.211909	2.55	1.57	1	2	1
15	33046	619	58	2	<0.01	1	99.7	0.322061	0	2.73	1.64	1	2	1
16	40280	1069	1060	1	1	1	99.8	0.093371	0.093371	2.69	1.62	1	2	1
17	26788	18342	2111	27	<0.01	1	99.9	0.146987	0	2.03	1.38	1	2	1
18	92600	10200	<0.01	<0.01	<0.01	1	100	0	0	2.59	1.59	1	2	1
19	16000	3600	670	14	<0.01	1	99.6	0.387382	0	2.41	1.52	1	2	1
20	2091	149	20	3	<0.01	1	98.0	1.973684	0.000001	2.63	1.60	1	2	1

VI. CONCLUSIONS

The Duval triangle method identifies only the transformer fault, but it can’t determine the severity of the fault. Therefore, the thermodynamic approach is used to evaluate the severity of the fault. There are two starting decomposing material that are found in literature and the work tries to answer the question “Is the severity of the fault changed when the starting decomposing material changes?”. The results of this work demonstrated that the severity of the partial discharge fault in the transformer can be varied with the variability of the starting decomposing material. Based on the results, all of random selected cases had different partial discharge severity when using n-octane and Eicosane. Therefore, the starting decomposing material that was used in the thermodynamic approach had a significant effect in determining the severity of the partial discharge fault.

REFERENCES

[1]. S. Ghoneim, I. Taha, N.I. Elkalashy, “Integrated ANN-based proactive fault diagnostic scheme for power transformers using dissolved gas analysis”, IEEE Transactions on Dielectrics and Electrical Insulation, 23, (3), pp. 1838–1845, 2016.

[2]. IEEE Standard C57.104-2008: ‘IEEE guide for the interpretation of gases generated in oil-immersed transformers’, February 2009.

[3]. M. Duval, A. dePablo, “Interpretation of gas-in-oil analysis using new IEC publication 60599 and IEC TC 10 databases”, IEEE Electrical Insulation Magazine, 17, (2), pp. 31–41, 2001.

[4]. IEC Publication 599, “Interpretation of the analysis of gases in transformers and other oil-filled electrical equipment in service,” First Edition 1978.

[5]. I. Taha, S.Ghoneim, H.G. Zaini, “A fuzzy diagnostic system for incipient transformer faults based on DGA of the insulating transformer oils”, International Review of Electrical Engineering, 11, (3), pp. 305–313, 2016.

[6]. J.L.Guardado, J.L. Nared, P. Moreno, C.R. Fuerte, “A comparative study of neural network efficiency in power transformers diagnosis using dissolved gas analysis”, IEEE Transactions on Power Delivery, 16, (4), pp. 643–647, 2001.

[7]. Y.-C. Huang, H.-C. Sun, “Dissolved gas analysis of mineral oil for power transformer fault diagnosis using fuzzy logic”, IEEE Transactions on Dielectrics and Electrical Insulation, 20, (3), pp. 974–981, 2013.

[8]. K. Bacha, S. Souahlia, M. Gossa, “Power transformer fault diagnosis based on dissolved gas analysis by support vector machine”, Electric Power System Research, 83, (1), pp. 73–79, 2012.

[9]. C. Wei, W. Tang, Q. Wu, “Dissolved gas analysis method based on novel feature prioritisation and support vector machine”, IET Electric Power Applications, 8, (8), pp. 320–328, 2014.

[10] N. Abu Bakar, A. Abu-Siada, “Fuzzy logic approach for transformer remnant life prediction and asset management decision", IEEE Transactions on Dielectrics and Electrical Insulation, 23, (5), pp. 3199–3208, 2016.

[11] Jinzhong Li, Qiaogen Zhang, Ke Wang, Jianyi Wang, Tianchun Zhou, and Yiyi Zhang, “Optimal Dissolved Gas Ratios Selected by Genetic Algorithm for Power Transformer Fault Diagnosis Based on Support Vector Machine”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 23, No. 2; pp. 1198-1206, April 2016.

[12] Abdolrahman Peimankar, Stephen John Weddell, Thahirah Jalal, Andrew Craig Lapthorn, “Evolutionary multi-objective fault diagnosis of power transformers”, Swarm and Evolutionry Computation, 36, pp. 62–75, 2017.

[13] A. Samy, S. A. Ward and M. N. Ali, “Conventional Ratio and Artificial Intelligence (AI) Diagnostic methods for DGA in Electrical Transformers”, International Electrical Engineering Journal, Vol. 6, No. 12, pp. 2096-2102, 2015.

[14] Shufali A Wani, Md. Umer Farooque, Shakeb A. Khan, Dhawal Gupta, Md. Ajmal Khan, “Fault Severity Determination in Transformers Using Dissolved Gas Analysis(DGA)”, 2015 Annual IEEE India Conference (INDICON), New Delhi, India, 17-20 Dec. 2015.

[15] F. Jakob, J.J. Dukarm, “Thermodynamic estimation of transformer fault severity”, IEEE Transactions on Power Delivery, 30, (4), pp. 1941–1948, 2015.

[16] Md. Danish Eqbal, Shakeb Ahmad Khan, Tarikul Islam, “Transformer incipient fault diagnosis on the basis of energy-weighted DGA using an artificial neural network”, Turkish Journal in Electrical Engineering & Computer Science, 26: 77 , 88, 2018.

[17] Sherif. S. M. Ghoneim, “Intelligent prediction of transformer faults and severities based on dissolved gas analysis integrated with thermodynamics theory”, IET Science, Measurement & Technology, Volume: 12 , Issue: 3 , 5, pp. 388-394, 2018

[18] M. Duval “A review of faults detectable by gas-in-oil analysis in transformers”, IEEE Electrical Insulation Magazine,18 (3):pp. 8–17, 2002.

[19] Akbari, A. Setayeshmehr, H. Borsi, E. Gockenbach, “A Software Implementation of the Duval Triangle Method”, IEEE International Symposium on Electrical Insulation, Vancouver, BC, Canada, 9-12 June 2008.