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Fault Diagnosis of Oil-Immersed Power Transformer: A Case Study

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***Abstract*— This paper presents the assessment of fault severity within power transformers from Dissolved Gas Analysis (DGA) using Hydrocarbon(HC) Gas Score and Normalized Energy Intensity(NEI) score. The score enables it to indicate that the transformer is in a normal or abnormal state. Based on the score data, engineers can decide on which action to take on each transformer. The example case uses the DGA results of the transformer of a commercial building to assess the severity of the faults in the transformers according to the above scoring method.**

Keywords— Fault Severity, Dissolved Gas Analysis, Hydrocarbon Gas Score and NEI Score

I. INTRODUCTION

Faults within the transformer are caused by deterioration of the insulation, either liquid or solid insulation. The transformer oil is mainly made of petroleum oil which has been added with some additives suitable for both electrical insulator and thermal conductivity for heat transfer inside the transformer. Solid insulation is mainly kraft paper and cardboard. Transformer oil ruptures when an overheating point or electrical stress is exceeded from an overload or short-circuit current flowing through the transformer. The rupture of transformer oil produces hydrogen (H_2) gas, four hydrocarbon gases: methane (CH_4), ethane (C_2H_6), ethylene(C_2H_4) and acetylene(C_2H_2). Different gases occur at different temperatures because the breakdown of transformer oil into gas molecules uses different energy[1]. Dissolved gas analysis has evolved into the primary method of finding faults within transformers. This analytical method uses gas concentration in the oil to classify faults as partial discharge, overheating or arcing. The analysis of gas in oil yielded the following results:

- Identify whether there is some sign of fault occur in the transformer or not.
- If there is a fault, proceed to specify the type of fault.
- Prioritize transformer status based on fault type and expert experience.

The above results are lacking the severity of the fault. To determine the type of fault in accordance with IEEE C57.104-2019, use the Duval Triangle or Duval Pentagon method to determine the type of fault. Both of these methods divide the extent of hydrocarbon gas generation according to the energy of each fault.

Recent research has presented the use of Normalized Energy Intensity (NEI) to detect and assess fault severity in transformers from DGA results instead of comparing gas concentrations and raise rates with limit values. This method uses the index of the energy used in the gas formation from the fault measured on a transformer oil sample. This index responds to all kinds of faults from DGA values. The basic principle of this method is that the constant formation of gas accumulators from faults indicates a problem within the transformer or an overstress in the transformer[2].

II. MODEL OF GAS FORMATION FROM FAULT

The crude oil used for refining into transformer oil consists of approximately 3,600 different molecules. Most of them are hydrocarbons, paraffin, naphthene, or aromatic molecules of this group of compounds. The molecular model used to represent the transformer oil is shown in Figure 1.

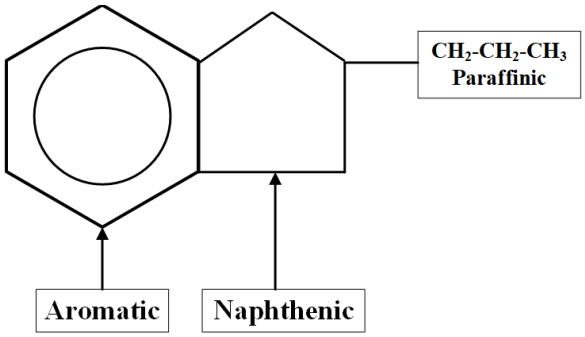

Fig. 1. Transformer oil molecule model

The molecules of transformer oil also contain atoms of other substances such as sulfur, oxygen and nitrogen. The molecular structure of aromatic rings and naphthene is more stable than the molecular structure of paraffin or paraffin compounds. The octane molecule (C_8H_{18}) is used to study breakdowns in transformer oil because the octane is derived from crude oil refined to make transformer oil and contains paraffin as a fault gas source[3].

$$C_8H_{18}(l) = CH_4(g) + C_7H_{14}(l) \quad (1)$$
$$C_8H_{18}(l) = C_2H_6(g) + C_6H_{12}(l) \quad (2)$$
$$C_8H_{18}(l) = C_2H_4(g) + C_6H_{14}(l) \quad (3)$$
$$C_8H_{18}(l) = H_2(g) + C_8H_{16}(l) \quad (4)$$
$$C_8H_{18}(l) = C_2H_2(g) + C_6H_{14}(l) + H_2(g) \quad (5)$$

where g is the gas, l is the liquid.

The energy of the above five reactions is determined from the enthalpy of each reaction. The enthalpy of substance B from substance A is the energy required to produce 1 mole (M_B g) of substance B from substance A, where M_B is the

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molecular mass of substance B in grams per mole. The enthalpy of gas formation from the octane decomposition is shown in Table 1.

TABLE I. ENTHALPY OF FAULTED GAS FORMATION

Reaction	Gas	ΔH_f°
(1)	CH_4	77.7
(2)	C_2H_6	93.5
(3)	C_2H_4	104.1
(4)	H_2	128.5
(5)	C_2H_2	278.3

The enthalpy in Table I uses to calculate the Normalized Energy Intensity (NEI).

III. NORMALIZED ENERGY INTENSITY (NEI)

The four hydrocarbon gas concentrations from the DGA results, methane, ethane, ethylene and acetylene, are used to calculate NEI according to equation (6), where NEI is in kJ/kL[4].

$$NEI = \frac{77.7CH_4 + 93.5C_2H_6 + 104.1C_2H_4 + 278.2C_2H_2}{22400} \quad (6)$$

CH_4, C_2H_6, C_2H_4 and C_2H_2 are the concentrations of each gas (µL/L). If the reported gas concentration is not determined at 273 K (0 °C), NEI must be multiplied by factor 273/(273+T), where T is the temperature given in the DGA report in °C.

ASTM D3612 requires reporting at 0 °C, while IEC 60567 requires reporting at 20 °C. The online DGA meter reports the temperature at the time of measurement. The calculated NEI responds to all kinds of faults[5].

IV. LIMIT VALUE ACCORDING TO THE O_2/N_2 RATIO

IEEE/PES Transformers Committee Working Group C57.104 conducted a compilation and analysis of a DGA database observing the effect of transformer life, MVA rating, voltage rating and O_2/N_2 ratio. One finding from the analysis of DGA results is that certain parameters, most notably the ratio of O_2/N_2 and the transformer age, have a large influence on the typical levels of gases. Other subsets of the data did not produces significance differences. It was found that the more oxygen-containing transformers, the less combustible gas. The balance of oxygen and nitrogen in the transformer depends on the transformer oil storage system. If it is an oil-immersed type transformer with a tank, the O_2/N_2 value is higher than the sealed, rubber bag, and nitrogen gas-filled type. The IEEE C57.104-2019 standard divides high and low oxygen transformers at a ratio of 0.2. If $O_2/N_2 > 0.2$, it is a transformer with a reservation tank. If $O_2/N_2 < 0.2$, it is a sealed transformer, rubber bag or nitrogen gas-filled type, a transformer with low oxygen content. Table II shows the gas limits in oil, divided into 2 sections: low oxygen and high oxygen, which are clearly different.

TABLE II. DGA LIMITS FOR HYDROCARBON GAS

Group	Gas	L_1	L_2	L_3
High-O_2	Methane	18	37	102
High-O_2	Ethane	24	56	146
High-O_2	Ethylene	43	78	179
Low-O_2	Methane	72	120	221
Low-O_2	Ethane	120	227	433
Low-O_2	Ethylene	44	91	295
All	Acetylene	2	10	36

The limits of NEI values are shown in Table III.

TABLE III. NEI LIMIT VALUES

Group	L_1	L_2	L_3
High-O_2	0.2	0.39	0.72
Low-O_2	0.51	1.02	1.87

V. DETERMINING THE DGA SCORE

This paper compares faults severity with two scorings methods: the hydrocarbon gas score and NEI score. It uses the limit values from tables II and III. The details of the scoring principle are as follows[6].

A. Assign limits for each transformer

Determine the transformer's O_2/N_2 ratio to identify it as a high- or low-oxygen type. According to Tables II and III values, the ratios above were taken to determine the hydrocarbon gas concentration limit and the NEI limit.

B. Determine the hydrocarbon gas score

Determine the score from the report of the hydrocarbon gas concentration of each transformer oil sample (x) and the L_1, L_2 and L_3 limits under the following conditions:

- If $x \geqslant L_3$, the gas score is 4.00.
- If $L_2 \leqslant x \leqslant L_3$, the gas score is $3 + \frac{x - L_2}{L_3 - L_2}$
- If $L_1 \leqslant x \leqslant L_2$, the gas score is $2 + \frac{x - L_1}{L_2 - L_1}$
- If $x < L_1$, the gas score is $1 + \frac{x}{L_1}$

The hydrocarbon gas score of the oil sample is determined from the maximum value of the individual gas score.

C. Determine the NEI score

The NEI value is calculated from the hydrocarbon gas concentration in the transformer oil sample and the NEI score of the oil sample is calculated. Compare the NEI value given as x with the NEI limit value of the transformer in Table III (L_1, L_2, L_3). Follow the conditions in section B to find the NEI score.

D. Determine the type of fault from the DGA results

If the transformer oil sample has methane, ethylene or acetylene concentration of at least 10 µL/L, use the Duval Triangle or Duval Pentagon method to determine the type of fault.

VI. CASE STUDY

The transformers of a large commercial building

A large building in Bangkok has a single line diagram as shown in Figure 2.

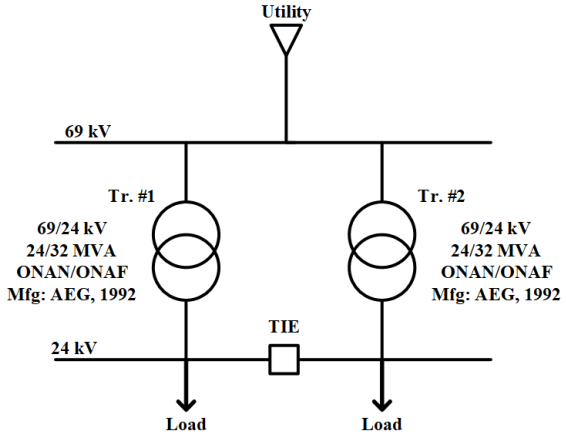

Fig. 2. Single line diagram of a large commercial building

Transformers 1 and 2 were produced by AEG in 1992. The transformers' ratings are as follows: 24/32 MVA 69/24 kV ONAN/ONAF. The transformer oil was sampling 3 times, the first on 8th September 2015, the second on 22rd October 2019 and the last on 30th October 2019[7].

Transformer no.1

The DGA resuls of transformer no.1 are given in Table IV.

TABLE IV. DGA DATA OF THE TRANSFORMER NO.1

Gas	Dissolved Gas Concentration(ppm)		
	8-Sep-15	22-Oct-19	26-Oct-19
O_2	15256	11156	10516
N_2	63311	42639	42674
Methane(CH_4)	8	2398	2447
Ethane(C_2H_6)	1	652	680
Ethylene(C_2H_4)	11	9	10
Acetylene(C_2H_2)	0	13	13

The DGA results of 26th October 2019 found that the O_2/N_2 ratio was 0.25, indicating that this transformer has a conservator. Use the limit values in Tables II and III; the gas score can be calculated as shown in Tables V and VI. The individual hydrogen gas scores are shown in Table V, and the maximum hydrocarbon gas scores of each sample date are used as the hydrocarbon gas scores.

TABLE V. INDIVIDUAL HYDROCARBON GAS SCORE

Gas	8-Sep-15	22-Oct-19	26-Oct-19
Methane(CH_4)	1.44	4.00	4.00
Ethane(C_2H_6)	1.04	4.00	4.00
Ethylene(C_2H_4)	1.26	1.21	1.23
Acetylene(C_2H_2)	1.00	3.12	3.12

TABLE VI. HYDROCARBON GAS SCORE

	8-Sep-15	22-Oct-19	26-Oct-19
HC Gas Score	1.44	4.00	4.00

The hydrocarbon gas score increased from 1.44 on 8th September 2015 to 4.00 on 22nd October 2019. This value indicates that the transformer is in critical condition and must be out of service and taken for inspection urgently. NEI scores were calculated based on NEI values and used the NEI limits in Table III. Results are shown in Table VII.

TABLE VII. NEI VALUE AND NEI SCORE

	8-Sep-15	22-Oct-19	26-Oct-19
NEI	0.08	11.24	11.53
NEI Score	1.42	4.00	4.00

The results are consistent with the hydrocarbon gas score. The NEI rating is increased from 1.42 to 4.00, indicating a severe fault in the transformer. The methane ethylene and acetylene gas concentration were above 10 µL/L, so the Duval Triangle was used to determine the type of fault, as shown in Figure 3[8].

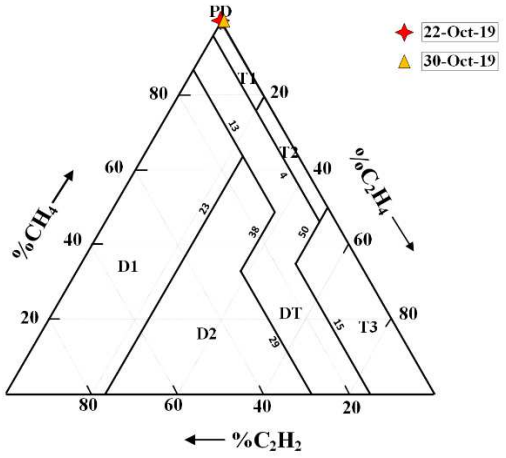

Fig. 3. Duval's triangle of Transfomer 1

The type of fault that can be obtained from the Duval Triangle is PD, which falls into the category of non-severe faults that do not correspond to the scores found above.

Transformer no.2

The DGA sample of transformer no.2 are given in Table VIII.

TABLE VIII. DGA DATA OF THE TRANSFORMER NO.2

Gas	Dissolved Gas Concentration(ppm)		
	8-Sep-15	22-Oct-19	26-Oct-19
O_2	1227	1661	1773
N_2	67656	44864	47518
Methane(CH_4)	67	2392	2790
Ethane(C_2H_6)	28	565	690
Ethylene(C_2H_4)	13	18	21
Acetylene(C_2H_2)	0	10	12

The DGA results of 26th October 2019 found that the O_2/N_2 ratio was 0.04, indicating that this transformer is a sealed type. Use the limit values in Tables II and III; the gas score can be calculated as shown in Tables IX and X.

TABLE IX. INDIVIDUAL HYDROCARBON GAS SCORE

Gas	8-Sep-15	22-Oct-19	26-Oct-19
Methane(CH_4)	1.93	4.00	4.00
Ethane(C_2H_6)	1.23	4.00	4.00
Ethylene(C_2H_4)	1.30	1.41	1.48
Acetylene(C_2H_2)	1.00	3.00	3.08

TABLE X. HYDROCARBON GAS SCORE

	8-Sep-15	22-Oct-19	26-Oct-19
HC Gas Score	1.93	4.00	4.00

The hydrocarbon gas score increased from 1.93 on 8th September 2015 to 4.00 on 22nd October 2019. This value indicates that the transformer is in critical condition as transformer 1. NEI scores were calculated based on NEI values and used the NEI limits in Table III. Results are shown in Table XI.

TABLE XI. NEI VALUE AND NEI SCORE

	8-Sep-15	22-Oct-19	26-Oct-19
NEI	0.41	10.86	12.80
NEI Score	1.80	4.00	4.00

The results are consistent with the hydrocarbon gas score. The NEI score is increased from 1.42 to 4.00, indicating a severe fault in the transformer. The methane gas ethylene and acetylene concentration were above 10 µL/L, so the Duval Triangle was used to determine the type of fault, as shown in Figure 4.

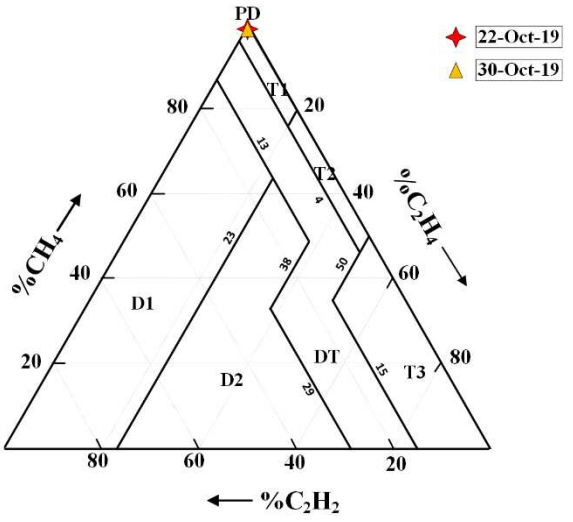

Fig. 4. Duval triangle of Transformer 2

VII. CONCLUSION

Fault severity assessments based on gas concentrations and the type of faults are based primarily on interpretations from the experience of DGA reading experts. This paper presents a method for estimating the severity of faults based on the energy of oil gasification that is measured to form the NEI equation. Fault severity assessments use two scoring methods, the Hydrocarbon Gas Score and the NEI Score, to compare them. The NEI score and the hydrocarbon gas score are consistent, but the NEI score is simple. It is appropriate to use it to assess the severity of the fault. The case study used the DGA results of a large building to be evaluated. Both scores were found to be 4.00, indicating that the transformer was in critical condition and had to turn off immediately and taken out for investigation.

The building manager prepares to inspect the transformer again during the long weekend while still using the transformer under normal load conditions. Until 1st December 2019, the transformer was short-circuited, causing power outages throughout the building for a long time. The building should stop using these transformers immediately and moved out for inspection.

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