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Mixture of Faults Identification on Power Transformers Using Multi-Method Dissolved Gas Analysis

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Abstract

Utilities rely on the various Dissolved Gas Analysis (DGA) interpretation methods to identify incipient fault within power transformers. However, confusion often arises due to the use of different DGA methods which can have different results or fail to detect mixture of faults (multiple faults). This paper implements the combination of Duval Triangle and Duval Pentagon as one of the most consistent methods to do fault identification based on DGA. Recent historical DGA data of generator step up high voltage power transformers and other several previously published historical data were collected and analyzed. This article aims to assist transformer asset manager in detecting mixture of faults using multi method. The use of combined Duval triangle and Pentagon method is done in accordance to the guideline in IEEE C57.104-2019

Keywords : Power Transformer, Dissolved Gas Analysis, Mixture of Faults, Fault Identification, Duval Triangle Method

1 Introduction

Power transformer is one of the most important electrical equipment in the power system. It functions to transform power from one voltage level to another voltage level. To prevent some electrical contact on the components in the transformer, insulator or dielectric material is needed, mainly paper immersed in insulating oil. Insulating oil allows for safe and reliable transmission of electrical energy [1].

The presence of dissolved gas in the insulating oil can be used as an indication of faults within the transformer. DGA (Dissolved Gas Analysis) is a transformer diagnostic method that is often done by utilities by looking at the gas condition in the insulating oil [2]. Utilities use the DGA test to schedule maintenance for transformers, check status of new and repaired units, and get the latest information about transformer conditions [3]. Generally, faults on power transformers are classified into two types, which are electrical faults like discharge and arcing, the other type is thermal faults (high and low thermal). If there are faults inside transformers, then some gasses would be formed in insulating oil [4].

Utilities rely on the DGA interpretation method from DGA standards to interpret the condition of transformers, but in many cases, misinterpretation often arises because several DGA methods resulting in different fault type, or even fail to detect mixture of faults (multiple faults) [5]. Several studies have been carried out to reduce misinterpretation and detect mixture of faults. A study in reference [6] uses the Duval triangle method for identification of thermal failure and partial discharge of transformer oil used in geothermal power plant UPJP Kamojang. A study in [7] proposed the integration of Duval Pentagon to the multi-method interpretation to improve the accuracy of dissolved gas analysis technique. A study from [8] shows the best conventional DGA method for detecting detailed faults in transformers are the Duval triangle and pentagon. A study in reference [9] developed an artificial neural network (ANN) based on the Duval pentagon method to enhance diagnostic capability and facilitate online monitoring of transformers, in this study, the diagnostic accuracy of ANN-based on the Duval pentagon is around 92%. A study in reference [5] has developed multiple faults detection based on Duval triangle 1 using a fuzzy inference system and ANN. All of the studies mentioned confirm that duval triangle and duval pentagon method have high accuracy for the identification of faults in transformers. However, the duval triangle and pentagon only identify single fault. Study in [5] developed mixture of faults using that is duval triangle 1, but the other high accuracy method that is duval pentagon has not been included.

This paper present a novel identification of mixture of faults from the DGA test using a combination of duval triangle method and duval pentagon method. To accomplish that, recent DGA data of high voltage power transformers are collected. The data consist of five hydrocarbons concentrations in ppm. The gas concentration would be interpreted with duval triangle and duval pentagon, then the results are compared. The use of duval triangle and pentagon method is in accordance to IEEE C57.104-2019 [2][10]. If mixture of faults are found with different types of basic faults like electrical faults and thermal faults, then subtracted (delta) of DGA data of present and the past is obtained to get more information on the analysis.

2 Method

2.1 Data Collecting and Cleaning

The first step is to acquire historical data of gas concentrations from DGA test of 5 transformers from observation and previous study, where transformer 1 and transformer 2 is generator step up transformers with the voltage of 10.5/157.5 kV, with the capacity of 153.75 MVA and 420 MVA. Both of transformer 1 and 2 are from Grati Gas and Steam Power Plant. Then transformers 3 data is from study reference [11], and transformers 4 and 5 are from study reference [12]. DGA measurement is applied weekly on transformers 1 and monthly for transformers 2 and 3 . In this study, the faults identification is using 5 hydrocarbon gases concentration values of H_2, CH_4 , C_2H_2, C_2H_4 , and C_2H_6.

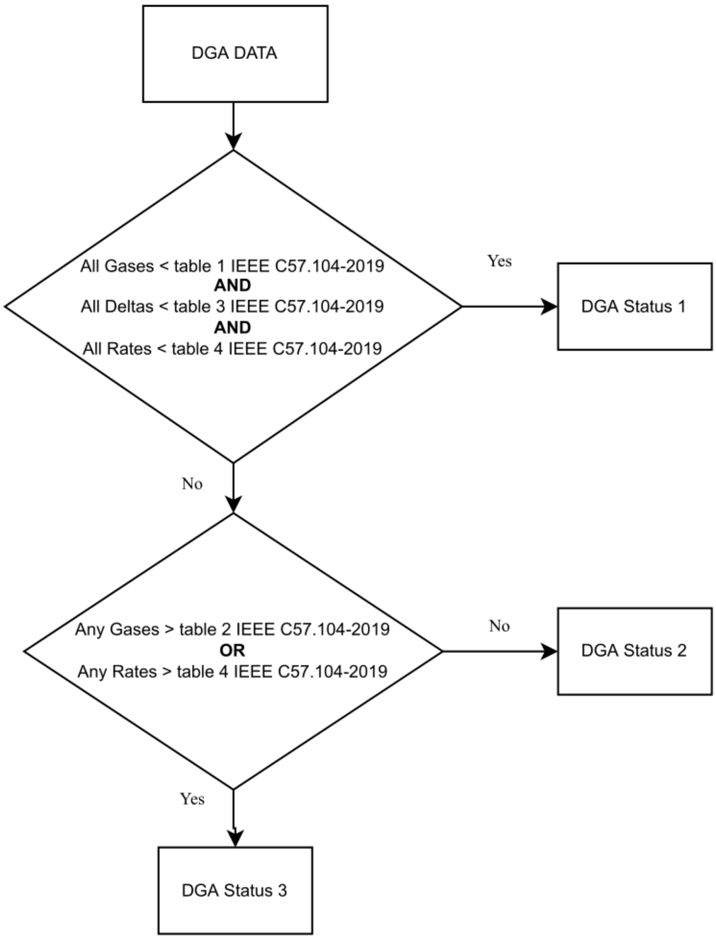

Figure 1: Flowchart of DGA Interpretation according to IEEE C57.104-2019

2.2 Checking DGA Status

After DGA data collected, the next step is to check the DGA status. There are 3 types of DGA status according to IEEE C57.104-2019. DGA status 1 means low gas concentration levels, and continue the normal operation of transformers. DGA status 2 indicates intermediate gas levels, and on this status transformers surveliance and DGA frequency should be increased. DGA status 3 indicates high gas concentration levels, and on this status faults identification should be performed [2]. Only DGA data with DGA status 3 is necessary to identify faults with fault identification methods such as Duval triangle and pentagon method.

2.3 Application of Duval Triangle

The duval triangle method uses percentage of 3 gases concentration as input parameter, there are 3 types of duval triangle for mineral oil. Depending on the triangle, different gas concentration is needed. For basic faults, duval triangle 1 is implemented, which uses the gas concentration percentage of CH_4, C_2H_4, and C_2H_2 as input parameter. The other two triangle types used to get additional information about sub-types of faults in mineral oil, which are duval triangle 4 and 5 [2][8]. In some cases, duval triangle 5 can identifying the basic faults like T2 and T3. The form of duval triangles are shown in Figure 2 [2].

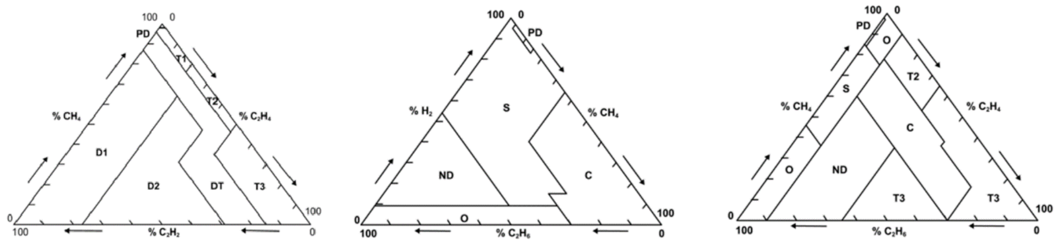

Figure 2: Duval Triangle 1, 4, and 5

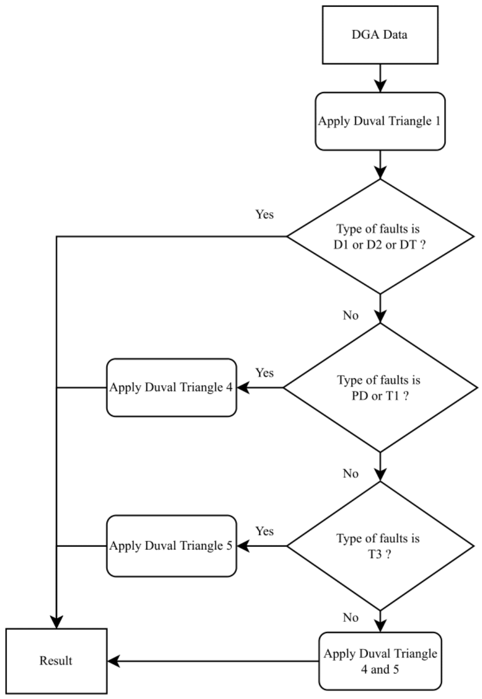

Figure 3: Flowchart of duval triangles 1,4, and 5 method implementation

After the data are collected, duval triangle 1 is implemented to find the basic faults of transformers. Accordint to the [2], there are some rules in using duval triangle 4 and 5. Triangle 4 and 5 can be used depends on the result of duval triangle 1. Figure 3 show the flowchart in duval triangles implementation on fault identification according IEEE C57.104-2019.

2.4 Application of Duval Pentagon

In Duval Pentagon, the percentage of 5 hydrocarbon gases concentration namely H2, CH4, C2H2, C2H4, and C2H6 are used as input parameter. Duval Pentagon 1 is used for the identification of basic faults, and for the identification of sub-types faults, duval pentagon 2 is used [13].

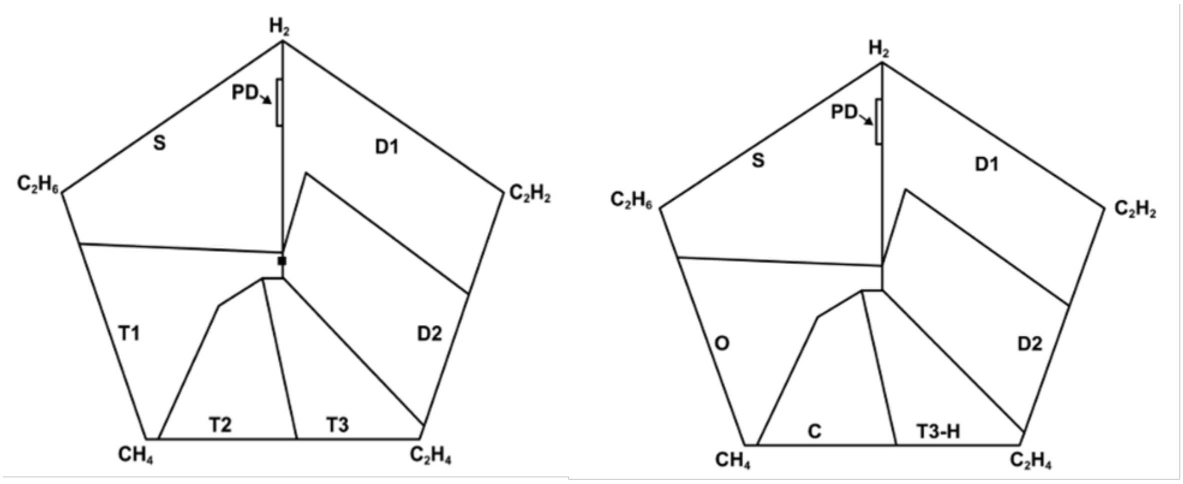

Figure 4: Duval Pentagon 1 and 2

Five hydrocarbon gases are plotted to pentagon, resulting in coordinates of five relative gas percentages. The next step is to find the centroid of the new pentagon by five relative gas percentage coordinates [4][13]. The area of pentagon can be found by using equation (1). The coordinated of centroid x (Cx) and centroid y (Cy) of pentagon are calculated using equation (2) and (3):

$$A = \frac{1}{2}\sum_{i-0}^{n-1}(x_i y_{i+1} - x_{i+1} y_i) \tag{1}$$

$$C_x = \frac{1}{6A}\sum_{i-0}^{n-1}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \tag{2}$$

$$C_y = \frac{1}{6A}\sum_{i-0}^{n-1}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \tag{3}$$

The equations are used to find Cx and Cy, then plotted to the Duval Pentagon 1 in Figure 4, resulting in identification of faults. If the results are thermal faults, duval pentagon 2 is used to find additional information of the faults [2]. Figure 5 explains the combined method of using duval pentagon 1 and 2. Only thermal faults on basic faults need to be identified with duval pentagon 2.

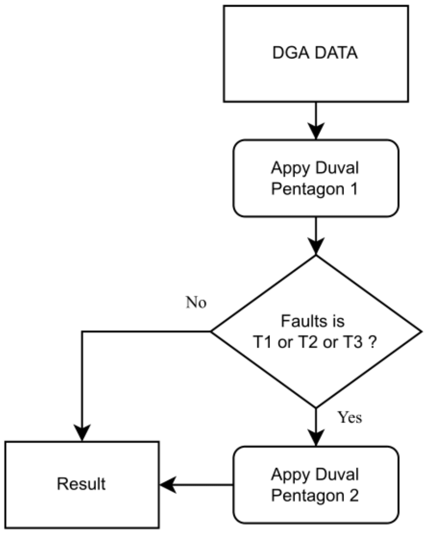

Figure 5: Flowchart method Duval pentagon

2.5 Identification of Additional Gas Using Delta Values

If the result of Duval triangle and Duval pentagon do not agree, delta values can be used to find the additional gases and faults. For this instance, previous DGA data has been collected. The concentration of X gases in ppm on X DGA data (n) is subtracted with the concentration of gases of previous DGA data (n-1). The notation n means number of DGA data that has been collected, and X means the types of gases that is calculated the delta.

$$DeltaX = X_n - X_{n-1} \tag{4}$$

If the result of delta values is negative, then it is replaced with zero. After that, the result of delta values is used on Duval triangle and pentagon. The method of finding additional faults from delta values show in Figure 6.

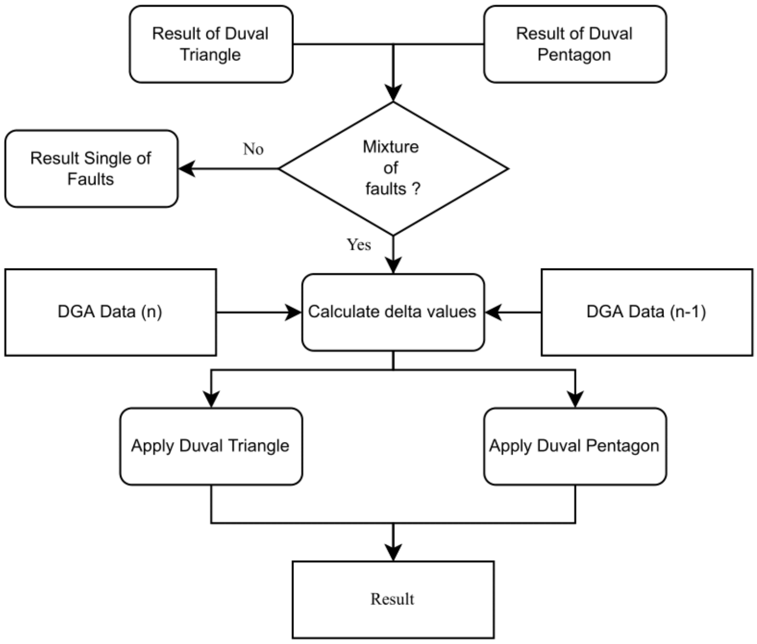

Figure 6: Flowchart of finding additional faults using delta values

3 Results and Discussion

Historical data of five concentration of gases were collected from five transformers. Following the methodology in section 2, the first is to check DGA status based on IEEE C57.104-2019. Then, for status 3 transformers, identification faults are done by using duval triangle and duval pentagon. Additional analysis is then done for the transformers with indication of mixture of faults.

3.1 DGA Status Based on IEEE C57.104-2019

The transformers must be checked for the DGA status before faults identification using Duval triangle and pentagon is implemented. The way to check DGA status shown on section 2.2. Table 1 shows result of the DGA status for 5 transformers observed.

Table 1: DGA Status According IEEE C57.104-2019

Transformers No	Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	DGA Status (IEEE C57.104-2019)
Transformers 1	November 2011	2	9	0	6	2	1
	August 2012	6	14	0	8	4	1
	June 2013	6	17	0	10	5	1
	June 2014	0	8	0	7	4	1
	August 2014	0	6	0	7	5	1
	December 2014	2	14	0	9	5	1
	January 2015	0	13	0	7	4	1
	November 2015	0	0	0	7	11	1
	June 2016	0	7	0	7	5	1
	December 2016	0	17	0	4	0	1
	August 2017	9	13	0	5	0	1
	April 2018	0	3	0	0	0	1
	October 2018	0	0	0	10	24	1
	January 2019	0	0	0	10	24	1
	March 2019	0	2	0	0	0	1
Transformers 2	July 2019	17	2	0	0	0	1
	September 2019	19	2	0	0	0	1
	January 2020	15	2	0	0	0	1
	January 2021	17	4	0	0	2	1
Transformers 3	June 2015	68	39	13	73	10	3
	June 2015	60	38	15	73	10	3
	July 2015	58	39	11	73	10	3
	July 2015	38	37	14	72	9	3
	August 2015	42	43	13	80	10	3
	August 2015	31	40	11	80	10	3
	September 2015	29	37	10	82	10	3
	September 2015	29	36	10	80	10	3
	October 2015	24	38	9	81	11	3
Transformers 4	May 2018	168	7	3	8	57	3
	October 2018	311	16	3	16	73	3
	January 2019	269	10	4	8	55	3
	April 2019	236	22	3	33	70	3
Transformers 5	June 2017	54	166	0	79	354	3
	May 2018	56	160	1	75	326	3
	October 2018	57	147	1	66	312	3

Transformers with DGA status 1 can continue the normal operation and routine DGA test, and only transformers with DGA status 3 that need to perform fault identification. Based on table 1, transformers 1 and 2 are on DGA status 1, which can continue normal operation without the need to implement duval triangle and pentagon to identify faults. The DGA status on transformers 3, 4, and 5 are on DGA status 3, which mean that the use of duval triangle and pentagon method to identify the faults are necessary.

3.2 Fault Identification using Duval Triangle

Table 2 shows the result of basic faults identification of transformers 3, 4 and 5 using duval triangle 1. The indication of fault on transformers 3 is thermal faults T3, while transformers 4 has indication of mix discharge and thermal fault or DT on May and October 2018, high discharge D2 are indicated at January 2019 and becoming thermal faults T3 at April 2019. Duval triangle 1 fault identification of Transformers 5 resulting on thermal faults T2. Following the guide [2], duval triangle 4 is implemented on transformers 5. While for duval triangle 5, there are 9 DGA data from transformers 3, 1 DGA data from transformers 4, and 3 DGA data from transformers 5.

According to table 4; the sub-types of faults are Not Defined or ND on all DGA data Transformers 5. The result of duval triangle 5 are shown on table 3, resulting in T3 for Transformers 3 which is same with basic faults from duval triangle 1 of transformers 3. Table 3 shows that result of duval triangle 5 on transformers 4 and 5 are ND which mean sub-types of faults on transformers 3, 4, and 5 can not be identify with duval triangle method.

Table 2: Result of Duval Triangle 1

Transformers	Date	CH_4	C_2H_2	C_2H_4	Faults
Transformers 3	June 2015	39	13	73	T3
	June 2015	38	15	73	T3
	July 2015	39	11	73	T3
	July 2015	37	14	72	T3
	August 2015	43	13	80	T3
	August 2015	40	11	80	T3
	September 2015	37	10	82	T3
	September 2015	36	10	80	T3
	October 2015	38	9	81	T3
Transformer 4	May 2018	7	3	8	DT
	October 2018	16	3	16	DT
	January 2019	10	4	8	D2
	April 2019	22	3	33	T3
Transformer 5	June 2017	166	0	79	T2
	May 2018	160	1	75	T2
	October 2018	147	1	66	T2

Table 3: Result of Duval Triangle 4

Transformers	Date	H_2	CH_4	C_2H_6	Faults
Transformers 5	June 2017	54	166	354	ND
	May 2018	56	160	326	ND
	October 2018	57	147	312	ND

Table 4: Result of Duval Triangle 5

Transformers	Date	H_2	CH_4	C_2H_6	Faults
Transformers 3	June 2015	39	13	73	T3
	June 2015	38	15	73	T3
	July 2015	39	11	73	T3
	July 2015	37	14	72	T3
	August 2015	43	13	80	T3
	August 2015	40	11	80	T3
	September 2015	37	10	82	T3
	September 2015	36	10	80	T3
	October 2015	38	9	81	T3
Transformers 4	April 2019	22	3	33	ND
Transformers 5	June 2017	166	0	79	ND
	May 2018	160	1	75	ND
	October 2018	147	1	66	ND

3.3 Fault Identification using Duval Pentagon

After identification using duval triangle method, the next method is Duval pentagon. Following the guide in [2], [13], the table 5 and table 6 show the result of faults identification using duval pentagon 1 and 2. Table 5 shows that fault identification of transformer 3 is thermal faults T3, while transformer 4 is Stray gassing (S), and transfomer 5 is thermal faults T1. There are 9 DGA data from transformers 3 and 3 data from transformers 5 that can be further analized using duval pentagon 2. The result of duval pentagon 2 is shown on Table 6, with the sub-types of faults of transformers 3 is T3-H and transformers 5 sub-types is O.

multirow

Table 5: Result of Duval Pentagon 1

Transformers	Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Faults
Transformers 3	June 2015	68	39	13	73	10	T3
	June 2015	60	38	15	73	10	T3
	July 2015	58	39	11	73	10	T3
	July 2015	38	37	14	72	9	T3
	August 2015	42	43	13	80	10	T3
	August 2015	31	40	11	80	10	T3
	September 2015	29	37	10	82	10	T3
	September 2015	29	36	10	80	10	T3
	October 2015	24	38	9	81	11	T3
Transformers 4	May 2018	168	7	3	8	57	S
	October 2018	311	16	3	16	73	S
	January 2019	269	10	4	8	55	S
	April 2019	236	22	3	33	70	S
Transformers 5	June 2017	54	166	0	79	354	T1
	May 2018	56	160	1	75	326	T1
	October 2018	57	147	1	66	312	T1

Table 6: Result of Duval Pentagon 2

Transformers	Date	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Faults
Transformers 3	June 2015	68	39	13	73	10	T3-H
	June 2015	60	38	15	73	10	T3-H
	July 2015	58	39	11	73	10	T3-H
	July 2015	38	37	14	72	9	T3-H
	August 2015	42	43	13	80	10	T3-H
	August 2015	31	40	11	80	10	T3-H
	September 2015	29	37	10	82	10	T3-H
	September 2015	29	36	10	80	10	T3-H
	October 2015	24	38	9	81	11	T3-H
Transformers 5	June 2017	54	166	0	79	354	O
	May 2018	56	160	1	75	326	O
	October 2018	57	147	1	66	312	O

3.4 Mixture of Faults Identification

After the implementation of Duval Triangle and Pentagon, two transformers have the indication of mixture of faults, which are transformers 4 and 5. Mixture of faults may happen if the identfication of faults using duval triangle and pentagon do not agree. In such case, delta values can help to identify the mixture of faults [2]. On table 7, the basic faults of thermal can be different types, T2 on duval triangle may result in T1 on duval pentagon, and S on duval pentagon may result in discharge or thermal faults on duval triangle .

From Table 7, the delta values result of duval triangle of transformers 4 on October 2018 is T2, which is different with duval pentagon result of S. The delta values result on January 2019 is D1 on duval triangle and pentagon. For data on April 2019, the delta values result of duval triangle and pentagon is T3.

The delta values result of duval triangle and pentagon for transformer 5 on May 2018 is D1. On October 2018 data, the delta value of duval triangle was not detected due to negative values or no additional gas, but on duval pentagon the delta values result is S.

The different basic faults on transformer 4 can happen because of the number of gas concentration used. Duval triangle 1 only use CH_4, C_2H_2, and C_2H_4 to identify basic faults. However, high concentration of H_2 affect the result of duval pentagon 1 making the centroid of duval pentagon tends to S region. Thermal faults T2 result may be different between duval triangle and pentagon. For DGA data on May 2018 and October 2018 of transformers 5, the result of duval triangle is T2, but on duval pentagon it is T1. It can happen because the concentration of C_2H_6 on the data. The duval triangle 1 does not use concentration of C_2H_6. In this case, the high concentration of C2H6 can be indication make the mixture of faults of thermal faults. Result of Delta values of transformers 4 at October 2018 show no additional gas on duval triangle and S on

Table 7: Transformers with the indication mixture of faults

Transformers	Date	Duval Triangle			Duval Pentagon		
		Basic Faults	Sub-types Faults	Delta Values Result	Basic Faults	Sub-types Faults	Delta Values Result
Transformers 4	October 2018	DT	-	T2	S	-	S
	January 2019	D2	-	D1	S	-	D1
	April 2019	T3	ND	T3	S	-	T3
Transformers 5	May 2018	T2	ND	D1	T1	O	D1
	October 2018	T2	ND	No Additional Gas	T1	O	S

duval pentagon. The result of this can be happen cause delta values are on zero ppm except for C_2H_6, so the additional gas on this data is C_2H_6, this delta values can't be use on duval triangle and would have S on duval pentagon.

The study in [8] reported that duval triangle method and duval pentagon method has high accuracy in faults identification of transformers. This study presents the development of using multi-method DGA interpretation from the combination of duval triangle and duval pentagon method with improvement from previous research. On the [6] duval triangle method can identify partial discharge and thermal failure, and from [9] the duval pentagon are use for base method for interpretation. In the result section, the duval triangle show the discharge and thermal faults to often be the identification result, but the duval pentagon may be more sensitive for identification of stray gassing. Some of faults identified with high H_2 concentration on duval triangle, are stray gassing on duval pentagon. This can happen because for basic faults identification (duval triangle 1 and pentagon 1), the gas input parameters are different. In this case, the use of combined method with further analysis of mixture of faults is necessary.

4 Conclusion

Analysis has been done on the historical DGA data of five power transformers. The use of combined Duval triangle and Pentagon method is done in accordance to the guideline in IEEE C57.104-2019. The analysis shows that generator step up transformers (transformer 1 and 2) resulting in status 1, with the recommendation of continue normal operation. Analysis on DGA of transformer 3, 4, and 5 resulting on status 3, which IEEE C57.104-2019 recommends to perform fault identification. Identification of mixture of faults is presented by using combined duval triangle and duval pentagon method. The result of duval triangle were compared to duval pentagon, and if it does not agree then it will be the indication of mixture of faults. From the power transformers studied, two transformers (four and five) indicate mixture of faults. The use of recent guideline in combined with identification of mixture of faults could benefit asset manager in taking appropriate action based on DGA assessment results.

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