

The Comparison of DGA Interpretation Techniques Application for Actual Failure Transformer Inspections Including Experience from Power Plants in Thailand

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Abstract: Dissolve gas analysis (DGA) is a diagnostic test technique applied for transformer condition evaluation. The interpretation of the dissolved gas results is a significant procedure to classify the incipient fault types in transformers. A variety of dissolved gas interpretation methods utilized for the same investigation case may give different fault type results. This paper investigates the performance of dissolved gas interpretation methods, including Doernenburg Ratio, Roger Ratio, IEC Ratio, Müller-Schlliesing and Soldner Method, Duval Triangle, and Duval Pentagon. The twenty-four failure transformer cases are used to evaluate the performance of the dissolved gas interpretation methods. The test result shows that the Duval pentagon interpretation technique shows the highest consistency interpretation. Besides, the Duval pentagon method demonstrates the ability to identify a normal aging problem of the transformer insulation.

Keywords: Diagnostic test technique; Dissolved gas analysis; Transformer insulation; Fault types

1. Introduction

The transformer plays a significant role in electrical power transmission and distribution systems. Currently, the role of the transformers is dramatically escalated due to the increase in electrical energy demand. Operating with very high reliability and accepted efficiency are key points of transformer utilization. However, it would seem impossible to maintain the transformer operation at full capacity during transformer service life. The main problems of the transformer failure are stem from the failure of the transformer insulation. Therefore, insulation testings and monitorings are very important to assure the operation of the transformers.

Transformer insulation conditions can be evaluated by applying various test techniques[1]. Partial discharge (PD) measurement, dielectric dissipation factor measurement, power factor testing, including winding turn ratio measurement, are generally performed in accordance with the planning strategy of the utility. Focusing on the insulating liquid, various tests such as breakdown voltage testing, measurement of water content, dielectric dissipation factor measurement, acidity test, and interfacial(IFT) test are recommended.

Moreover, dissolved gas measurement and furanic compound testing are essential methods that reveal the problems,i.e., electrical and thermal problems, occurring in a transformer [2]. The existence of dissolved gases in mineral oil caused by the decomposition process of cellulose and oil reduces the dielectric strength of such insulation material[3,4]. Various types of gases, i.e., ethylene (C_2H_4), ethane (C_2H_6), and methane (CH_4), including hydrogen (H_2) can be originated from the mineral oil degradation process [5]. In comparison, carbon dioxide (CO_2) and carbon monoxide (CO) are generally initiated by the degradation of cellulose [6]. Therefore, the Dissolved Gas Analysis (DGA) technique is beneficial for monitoring the

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transformer insulation. The brief procedure for conducting the DGA techniques is collecting the oil sample, dissolved gas extraction, and dissolved gas interpretation [7].

2. Interpretation Techniques

The DGA interpretation techniques have been suggested by international standards, e.g., IEEE C57.104:2008 [8] and IEC 60599:2015 [9], including national standards and utility methods. IEEE C57.104 recommends the key gases, the Doernenburg ratio, and the Roger ratio to interpret dissolved gas, whilst IEC 60599:2015 suggests the Duval triangle and IEC ratio for interpretation. Furthermore, Müller Schlliesing and Soldner technique is applied for dissolved gas interpretation in Germany. Lately, the Duval pentagon has been proposed to improve the ability of fault identification in a transformer. However, it seems that more inspection test results are needed to enhance the efficiency of the Duval pentagon. Due to the complexity of the DGA test technique and a variety of dissolved gas interpretation methods, therefore, to efficiently perform DGA needs a skilled person or even an expert to achieve the DGA test technique and interpretation. The dissolved gas interpretation techniques applied in this research work will be described below.

A. Doernenburg Ratio Method

The Doernenburg ratio method (DRM) is used as one of the international DGA interpretation techniques. Suppose at least one of these gas concentrations (H_2 , CH_4 , C_2H_4 , and C_2H_2) is more than twice the limit concentrations (L1), as shown in Table 1 [8], and the concentration of at least one of the two gases generating in any one of the four gas ratios is greater than the limit concentrations (L1) [8], the transformer is considered faulty. Then, determining if at least one of these gases in each ratio C_2H_6/C_2H_2 , C_2H_2/C_2H_4 , C_2H_2/CH_4 , and CH_4/H_2 , exceeds the limit concentrations (L1), the DRM is valid to analyze the fault types as demonstrated in Table 2.

B. IEC Ratio Method

IEC 60599 recommends the IEC ratio method (IRM) as one of the international DGA interpretation techniques [9]. Three gas ratios are applied to identify fault types demonstrated in Table 3. However, it needs to realize that some combinations of the gas ratios may drop outside the determined range. In such cases, the 3-dimension graphic in [9] is required to accomplish the interpretation task by which the feasible fault types can be specified as the zone or box closest to the undiagnosed case. Furthermore, some cases may not clearly identify if they fall in the overlap fault zones.

Table 1. Limit Concentrations of Dissolved Gas (L1) [8]

Key gas	Concentrations L1 (ppm)
Hydrogen	100
Methane	120
Carbon monoxide	350
Acetylene	1
Ethylene	50
Ethane	65

Table 2. Doernenburg Ratio Method Concentration Ratio [8]

Suggested fault diagnosis	$\frac{C_2H_2}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$
Thermal decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Partial discharge (low-intensity PD)	< 0.1	Not significant	< 0.3	> 0.4
Arcing (high-intensity PD)	> 0.1 to < 1.0	> 0.75	> 0.3	< 0.4

Table 3. The Failure Zones Indicated by The IEC Ratio [9]

Case	Fault Characteristic
PD	Partial Discharge
D1	Low energy discharges
D2	High energy discharges
DT	Combination of thermal faults and discharges
T1	Thermal faults (≤ 300 °C)
T2	Thermal faults (> 300 °C to ≤ 700 °C)
T3	Thermal faults (> 700 °C)

C. Roger Ratio Method

The Roger ratio method (RRM) employs the gas ratios quite similar to the ratios of the DRM, i.e., C_2H_2/C_2H_4 and CH_4/H_2 , except the ratio of C_2H_4/C_2H_6 [10] as represented in Table 4. Applying this method, some fault cases may not be identified if at least one of the gas concentration ratios is not relevant to the archetypal gas ratio concentration, as presented in Table 4. Moreover, the RRM method application may cause misinterpretation in case of the gas concentration less than the normal values [11].

D. Müller, Schlliesing and Soldner Method

Müller, Schlliesing, and Soldner Method (MSSM) employs seven gases-forming five gas ratios exhibited in Table 5 for interpretation of dissolved gas test results. Because the MSSM uses more gases for DGA interpretation compared with other DGA interpretation methods, it may cause difficulty, especially for the laboratories that are not capable of all required gas extractions.

Table 4. Roger Ratio Method [8]

Suggested fault diagnosis	Gas ratio		
	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
Unit normal	< 0.1	> 0.1 to < 1.0	< 1.0
Low-energy density arcing-PD	< 0.1	< 0.1	< 1.0
Arcing-High energy discharge	0.1 to 0.3	0.1 to 1.0	> 3.0
Low temperature thermal	< 0.1	> 0.1 to < 1.0	1.0 to 3.0
Thermal < 700 °C	< 0.1	> 1.0	1.0 to 3.0
Thermal > 700 °C	< 0.1	> 1.0	> 3.0

Table 5. Müller, Schlliesing and Soldner ratio method [12]

Ratio ranges	Ratio numbers				
	$\frac{C_2H_2}{C_2H_4}$	$\frac{H_2}{C_2H_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_4}{C_2H_2}$	$\frac{CO_2}{CO}$
< 0.3	0	0	0	0	1
0.3 to < 1.0	1	0	0	1	1
1.0 to < 3.0	1	1	1	2	1
3.0 to < 10.0	2	2	1	3	0
≥ 10.0	2	3	1	3	2
Diagnosis	Number sequences				
Normal ageing of insulants	0	0	0	0	0
High energy discharge	2	1	1	2, 3	1
Low energy discharge	2	2	1	2, 3	1
High energy - partial discharge	1	3	0	n.i.	0
Low energy - partial discharge	0	3	0	n.i.	0
Local overheating < 300 °C	0	0	0	1	2
Local overheating 300 to 1000 °C	0	0	1	2	2
Local overheating > 1000 °C	1	0	1	2, 3	2
Local overheating and Discharge	1	1	1	2	2
Local overheating and partial Discharge	0	3	1	2	2

Note: n.i. = no indicative

E. Duval Triangle Method (DTM)

Michel Duval invented the Duval triangle method (DTM) in 1974 for the interpretation of dissolved gases within mineral oil used in a mineral oil-filled transformer. Three gases, i.e., Methane, Ethylene, and Acetylene, are employed to identify fault types [13,14]. The percentage of the gas concentration obtained from the calculation is plotted into the Duval triangle containing seven section areas, as represented in Fig. 1. The pointing zone indicates the fault expected to happen in a transformer. Like the RRM, the DTM is not suitable for applying with a very low gas level. The DTM always identifies a fault problem in the transformer, notwithstanding the insulation system in the transformer is in normal aging condition. It may misguide the maintenance planning of the transformers under-investigated. According to [15], the DTM provided a higher DGA interpretation accuracy than other interpretation methods.

F. Duval Pentagon Method

Recently, Michel Duval proposed the Duval pentagon method (DPM) developed based on the Duval triangle. Two additional gases, including Hydrogen and Ethane, beneficial to separate PD phenomena out of the thermal fault at low energy, are utilized in the DPM applied for mineral oil problem investigation[16,17]. Besides, the stray gas zone (S) related to the gas generation under normal operation is introduced in the Duval pentagon, which escalates this method's capability to categorize the normal aging condition of the insulation used in a transformer [18]. The high accuracy fault identification in the transformer by applying the DPM compared with other methods is reported in [19].

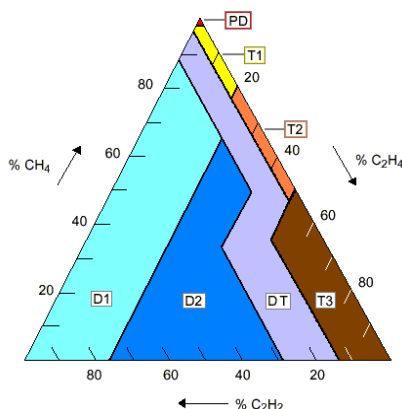


Figure 1. Duval triangle 1 for mineral oil [13]

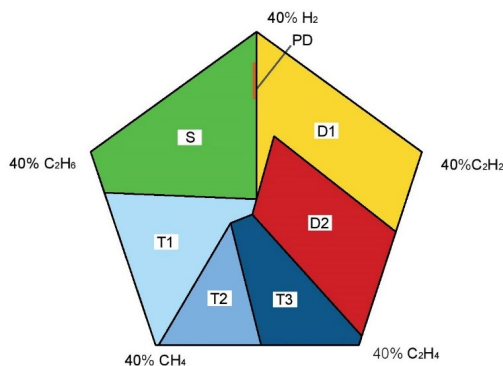


Figure 2. Duval pentagon 1 for mineral oil [21]

The DPM uses all five hydrocarbon gases, namely, CH₄, C₂H₂, C₂H₄, C₂H₆, and H₂, including the total gases expressed in percent as presented. The axes of the pentagon cover the range from 0 to 100%, by which the midpoint of the pentagon is defined as the starting point. The centroid of the pentagon is computed and plotted on the Duval pentagon [20]. The type of fault is specified based on the failure zone, as represented in Figure 2.

3. Test Method

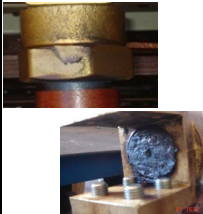
Before evaluating the performance of the investigated dissolved gas interpretation methods, the mentioned parameters identifying the fault types were marginally modified to six fault types, i.e., PD, T1, T2, T3, D1, and D2, respectively, for identifying fault cases summarized in Table 6. Then, the 24 cases of the failure transformers acquired from the opened tank inspection and the academic references [22-32] were used for this procedure. The opened tank failure transformers (case studies 1-5) illustrated in Table 7 have been examined by the authors and the maintenance utility staff.

According to evidence from the inspection of the opened tank failure transformers, case studies 1, 4, and 5 clearly show a high amount of C₂H₂, which may lead to thermal breakdown of the transformer insulation in a short time of transformer operation. Case studies 2 and 3 depict the bad contact problems leading to the first state of overheating; in these cases, the amount of C₂H₂ is less than 1.

Table 6. Grouping for Fault Type Codes for This Research

Methods	Fault types					
	PD	D1	D2	T1	T2	T3
DRM	Partial discharge (low-intensity PD)	Arcing (high-intensity PD)	Arcing (high-intensity PD)	Thermal decomposition	Thermal decomposition	Thermal decomposition
RRM	Low energy density arcing	Low energy density arcing	Arcing – High energy discharge	Low temperature thermal	Thermal < 700 °C	Thermal > 700 °C
IRM	Partial Discharge	Discharges of low energy	High energy discharge	Thermal faults not exceeding 700 °C	Thermal faults exceeding 300 °C but not exceeding 700 °C	Thermal faults exceeding 700 °C
MSSM	Partial Discharge with low energy Partial Discharge with high energy	Discharges of low energy	Discharge of high energy	Local overheating up to 300 °C	Local overheating up to 300 °C	Local overheating from 300 °C to 1000 °C Local overheating over 1000 °C
DTM	Partial Discharge	Discharges of low energy	High energy discharge	Thermal faults not exceeding 300 °C	Thermal faults exceeding 300 °C but not exceeding 700 °C	Thermal faults exceeding 700 °C
DPM	Partial Discharge	Discharges of low energy	High energy discharge	Thermal faults not exceeding 300 °C	Thermal faults exceeding 300 °C but not exceeding 700 °C	Thermal faults exceeding 700 °C
DPM	Partial Discharge	Discharges of low energy	High energy discharge	Thermal faults not exceeding 300 °C	Thermal faults exceeding 300 °C but not exceeding 700 °C	Thermal faults exceeding 700 °C

Table 7. The Opened Tank Transformer Case Studies and Dissolved Gas Results

Case study	Rate capacity	Rated voltage	DGA problem evaluation	Problem analytic after inspection of the opened tank failure transformer	Pieces of evidence from the inspection of the opened tank failure transformer	Dissolved gas (ppm)	
1	2,000 kVA	22 kV / 400V	Overheat at the insulation paper	- High temperature at the insulation paper - Loss of paper characteristic - Carbon product		H ₂	31
						CH ₄	3
						C ₂ H ₆	8
						C ₂ H ₄	46
						C ₂ H ₂	67
						CO	71
						CO ₂	4,397
2	500 kVA	22 kV / 416 V	Overheat (at the connection)	- Loose of connection - Overheat (at the connection)		H ₂	< 1
						CH ₄	100
						C ₂ H ₆	218
						C ₂ H ₄	30
						C ₂ H ₂	<1
						CO	471
						CO ₂	2,968
3	2,240 kVA	15 kV / 400 V	Overheat (at the connection joints)	- Overheat (at the connection joints) - Carbon product		H ₂	55
						CH ₄	112
						C ₂ H ₆	26
						C ₂ H ₄	129
						C ₂ H ₂	< 1
						CO	1,608
						CO ₂	8,272
4	2,000 kVA	6.6 kV / 400 V	Overheat	- Overheat at the clamp and the lead - Loss of connection characteristic - Arcing		H ₂	550
						CH ₄	5,679
						C ₂ H ₆	6,346
						C ₂ H ₄	5,190
						C ₂ H ₂	82
						CO	549
						CO ₂	10,780
5	9,600 kVA	22 kV / 1,100 V	Overheat	- Overheat at sleeve the wire lead between primary coil phases - Burn - Loss of paper characteristic		H ₂	70
						CH ₄	89
						C ₂ H ₆	73
						C ₂ H ₄	89
						C ₂ H ₂	3
						CO	429
						CO ₂	3,187

4. Analysis Method

The performance of the investigated DGA interpretation methods, as described in Table 8, was evaluated with the twenty-four-fault cases. Then, the percentages of successful prediction, including the consistency, are computed by equations below:

$$\% \text{Successful prediction} = \frac{\text{number of correct prediction}}{\text{number of prediction}} \times 100 \quad (1)$$

$$\% \text{Consistency} = \frac{\text{number of correct prediction}}{\text{number of case study}} \times 100 \quad (2)$$

The evaluated results summarized in Table 8 reveal that the Duval pentagon method (DPM) contributed the highest consistency for DGA interpretation results compared with DTM, DRM, RRM, IRM, and MSSM, respectively. From Table 8, the RRM yielded a more successful prediction than the DPM if the test was considered only for the predictable fault cases. However, when considering all of the case studies represented with the percentage of consistency, this value of RRM will reduce because RRM could not provide the interpretation result for some case studies. Moreover, when the normal aging and the fault types of the transformer insulation are considered, the percentage of the consistency of DTM and IRM would decrease because they could not classify the normal aging problem.

Table 8. Successful Prediction Comparison of The Investigated Interpretation Techniques

Method	N	No	Nc	% Successful prediction	% Consistency
DRM	22	2	17	77	71
RRM	17	7	17	100	71
IRM	17	7	10	59	42
MSSM	9	15	5	56	21
DTM	24	0	18	75	75
DPM	24	0	21	88	88

Note: N = Number of predictions
Nc = Number of correct predictions
No = Number of no prediction

5. Conclusion

According to the test results, the Duval pentagon method applied for DGA interpretation provided the highest consistency. The Duval pentagon method was developed based on the Duval Triangle. The Duval pentagon method also provided the stray gas zone directly associated with the normal condition of the transformer insulation. The strengths and shortcomings of the investigated DGA interpretation method are also detailed. The Duval pentagon method is a relatively new method having great potential. Nevertheless, the Duval pentagon method requires further field data to escalate the interpretation validity, especially when faults and normal aging of the transformer insulation are taken to account.

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