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# Use of dissolved gas analysis methods as tools for monitoring the state of health of power transformers installed on the electrical network in the northern shore of the large metropolis of Abidjan

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**ABSTRACT:** The liquid-insulated power transformer is the most critical and expensive component of the power supply system. In order to improve monitoring of the state of health of these devices (transformers) installed on the power grid in the bank of the large metropolis of Abidjan, dissolved gas analysis (DGA) was used. Conventional interpretation techniques were developed to diagnose transformer oil. The database we used consists of those of the Compagnie Ivoirienne d'Electricité (CIE) in 2018. It includes 25 samples containing analysis of the five main dissolved gases (H2, CH4, C2H2, C2H4, C2H6). The five defect classes we considered, namely partial discharge (PD), D1 and D2 electrical defects, T1&T2 and T3 thermal defects, are taken from the IEC and IEEE. For interpretation, five methods were adopted, namely the IEC, Doenenburg, Rogers criteria using the ppm gas concentration ratio technique, the Duval triangle using percentage gas concentrations and the IEEE criterion using ppm gas concentrations. The highest success rate of 72% was obtained when using the Duval triangle criterion. But the greatest consistency with a rate of over 70% was observed using the IEC ratio criterion.

**KEYWORDS:** power transformer, dissolved gas analysis, diagnostics, conventional methods, North Abidjan.

## 1 INTRODUCTION

Power plants in Côte d'Ivoire are mainly located in the south of the country. In Abidjan, around 400 MW are exchanged with other peak load regions. In order to improve the quality of power supply, it is necessary to significantly expand the national power grid. This achievement will make it possible to comply with the standard "No interruption of supply during an incident on one of the elements of the electrical network" and to stabilize the electrical network system [1]. Table 1 shows the various existing substations and lines and their color codes planned in the transmission network by 2030.

***Table 1. Electricity grid system in Côte d'Ivoire planned for 2030 [1]***

| Posts | | | Lines | | |
|---|---|---|---|---|---|
| Tension | Color code | Condition | Tension | Color code | Condition |
| 225 / 90 HTA | | Existing | 225 kV | | Existing |
| 90 HTA | | Existing | 90 kV | | Existing |
| 330 / 400 HTA | | Existing | 330 kV | | Existing |
| 400 / 225 HTA | | Existing | 400 kV | | Existing |
| 225 / 90 HTA | | Project | 225 kV | | Existing |
| 90 HTA | | Project | 225 kV | | Project |
| 330 / 400 HTA | | Project | 90 kV | | Project |
| 400 / 225 HTA | | Project | 330 kV | | Project |

Abidjan is traditionally divided into two parts, "North Abidjan " and "South Abidjan ", on either side of the Ebrié lagoon. "North Abidjan " comprises fourteen (14) communes, including the largest and most popular, Yopougon. The population of this area is growing, and by 2021 will have reached 5238986 inhabitants, almost one-sixth (1/6) of the national population of Côte d'Ivoire [2]. ]. In addition to its population, the area is home to the largest industrial zone. Electricity consumption is therefore high and an integral part of the inhabitants' lives. The number of transformers will continue to grow as the area increases over the years [3]. This means that electricity production and transmission companies, such as the Compagnie Ivoirienne d'Electricité (CIE), have to provide a permanent service, especially for strategic infrastructures. Power supply interruptions are generally caused by obsolete transformers, which can cause irreversible damage. The power transformer is the most critical element in the electricity transmission system [4] [5]. Figure 1 illustrates the various transformer installations in the northern part of greater Abidjan.

Their safe and stable operation therefore plays an important role in the safe, stable and reliable operation of the entire power grid [4] [5]. During operation of power transformers, various failures can occur due to destruction or inappropriate installation [7] [8] [9] Its failure not only affects the availability of electrical energy, but also leads to very heavy technical, financial, commercial and environmental losses [10]. The need to detect and identify latent faults at an early stage, so that preventive action can be taken, is therefore extremely useful [11] [12] [13] [14] [15]. The paper-oil insulation system is an important accessory for power transformers, used to insulate high-voltage conductors through a steel tank [16] [17] ]. It is estimated that the oil in the transformer contains around 70% of the diagnostic information available for transformers [18] just like the blood in the human body. The reliability of power transformers depends on the preventive diagnosis of their paper-oil insulation system against electrical and thermal faults, which can considerably reduce their service life [14] [19]. Good diagnostic methods are essential for effective transformer maintenance. Dissolved gas analysis is one of the best ways of detecting a number of internal faults in transformers. [20] [21]. Dissolved gas analysis (DGA) is an important measure in the life cycle management of transformers. Correct interpretation of dissolved gas analysis can provide valuable information on the health of transformers. In fact, it enables us to identify and interpret faults (thermal and electrical) and the source of their creation, with a view to preventing any malfunctions at an early stage. Several methods have been proposed for moving from analysis results to diagnostic interpretation. This article is dedicated to the application of the most popular methods: Duval's graphical methods (triangle and pentagon), Dornenburg's ratios, Rogers' ratios, IEC 60599, the key gas method and the method prescribed by IEEE Standard C57. 104. The aim of these methods is to determine the causes of malfunctions, based on observations (measurement and analysis data) and observed symptoms (anomalies). In this study, we will diagnose 25 transformers installed in the northern zone of Abidjan (Côte d'Ivoire), using various conventional methods for interpreting gases dissolved in transformer oil. These are mainly the IEC 60599, IEEE C57.104, Doernenburg, Rogers and Duval triangle methods

## 2 DISSOLVED GAS ANALYSIS (DGA)

During operation, power transformers are subjected to electrical, thermal and environmental stresses, which can lead to the degradation of insulating materials [22]. Insulation is an important part of a power transformer, and both solid and liquid insulation are widely used. Thanks to early detection of any internal faults developing in power transformers, the expense of unplanned power transformer breakdowns is often reduced. Gases dissolve in transformer oil during transformer operation. These gases have evolved as a result of transformer faults such as arcing, partial discharge, overheating of transformer oil or overheating of insulating paper (cellulose). Different types of gas will be at different concentration levels depending on the nature of the faults developing in a transformer. Among dissolved gases, flammable gases (hydrocarbon gases) are very critical, and any quantum leap in the concentration levels of these gases can lead to a severe/destructive type of transformer fault. Combustible gases such as $H_2$ (hydrogen), $C_2H_6$ (ethane), $C_2H_4$ (ethylene) and $C_2H_2$ (acetylene) typically appear in transformer oil at very low concentrations under normal conditions and are easily detected in ppm by dissolved gas analysis (DGA) [23] [22].

A mixture of gas ratios in relative proportion is used to establish a defect. AGD is performed in accordance with IS-10593 or ASTM D3612 or IEC 60567 and IEC-60599.

## 3 TRANSFORMER FAULTS

The different types of faults that occur in the transformer could be detected by the DGA. IEC 60599 classifies transformer faults detectable by gas analysis into two categories. These two main categories can be further classified into 6 types of transformer faults, depending on the magnitudes of the fault energy [24] [23]:

- Partial discharges (PD)
- Low power discharge
- High power discharge
- Thermal faults with temperatures below 300°C
- Thermal faults with temperatures between 300°C and 700°C
- Thermal faults with temperatures above 700°C

Various diagnostic schemes have been developed for DGA interpretation. These methods attempt to map relationships between gases and fault conditions, some of which are obvious and some of which may not be apparent. The assessment was simplified by looking at the key gases and associated condition as shown in Table 2.

*Table 2. Common Fault Types and Key Gases in DGA [25]*

| Working conditions | Interpretations |
|---|---|
| 1. Nitrogen more 5% or less oxygen | Normal running |
| 2. Nitrogen, carbon monoxide and carbon dioxide | Insulation of transformer windings overheated; the key gas is carbon monoxide |
| 3. Nitrogen, ethylene and methane - some hydrogen and ethane | Transformer oil is overheated; minor defect causing oil failure. The key gas is ethylene |
| 4. Nitrogen, hydrogen, small amounts of ethane and ethylene | Corona discharge in oil; the key gas is hydrogen |
| 5. Same as #4; with carbon dioxide and carbon monoxide | Corona involving paper insulation; the key gas is hydrogen |
| 6. Nitrogen, high hydrogen and acetylene; small amounts of methane and ethylene | High energy electric arc; the key gas is acetylene |
| 7. Same as #6 with carbon dioxide and carbon monoxide | High energy arc involves paper winding insulation; the key gas is acetylene |

## 4 MATERIALS AND METHODS

### 4.1 MATERIALS

The materials used were oils taken from 25 transformers in the electricity network on the north bank of the large metropolis Abidjan. The concentrations of the main dissolved gases in the samples taken from CIE (Compagnie Ivoirienne d'Electricité) transformers in ppm and the actual defect of each sample used as a database are presented in Table 3 [26]. It should be noted that these gases are obtained by gas chromatography and the defects are interpreted by experts. The different key gases dissolved in power transformer oil are. The main gases produced are methane ($CH_4$), ethane ($C_2H_6$), ethylene ($C_2H_4$), acetylene ($C_2H_2$) hydrogen ($H_2$), carbon monoxide and carbon dioxide (CO, $CO_2$) [27].

*Table 3. Dissolved gas concentrations and faults in Abidjan North transformers [26]*

| Site | Dissolved gas | | | | | | | | | Recorded faults |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $CO$ | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | TDCG | 2-FAL | |
| **TFO1** | 3395 | 404.9 | 151.9 | 9.6 | 44.9 | 6.6 | 0.2 | 618 | 0.00 | **DP** |
| **TFO2** | 2794 | 345.5 | 257.3 | 11.2 | 41.5 | 7 | 0.3 | 663 | 0.00 | **DP** |
| **TFO3** | 8582 | 358.7 | 180.2 | 210.1 | 680.8 | 16.9 | <0.1 | 1447 | 0.14 | **Type T3 and T1-T2 overheating** |
| **TFO4** | 215 | 40.5 | 5.5 | 0.9 | 0.1 | 0.1 | 0.1 | 47 | 0.00 | **Overheating** |
| **TFO5** | 1931 | 643.5 | 26.1 | 12.0 | 25.6 | 2.4 | 0.2 | 710 | 0.00 | **Overheating** |
| **TFO6** | 6964 | 327.8 | 6.7 | 4.3 | 2.6 | 29.5 | 0.2 | 371 | 0.09 | **Overheating** |
| **TFO7** | 1794 | 530.5 | 16 | 6.2 | 1 | 2.2 | <0.1 | 556 | 0.00 | **Overheating** |
| **TFO8** | 1857 | 572.8 | 19.8 | 23 | 54.3 | 2.8 | <0.1 | 673 | 0.00 | **Overheating** |
| **TFO9** | 1934 | 516.3 | 9.0 | 6.0 | 1.1 | 3.2 | <0.1 | 536 | 0.00 | **Overheating** |
| **TFO10** | 1259 | 142.9 | 200.5 | 7.5 | 31.1 | 5.1 | 0.4 | 388 | 0.00 | **Overheating** |
| **TFO11** | 3617 | 476.7 | 164.6 | 83.9 | 329.4 | 86.3 | 4.3 | 1145 | 0.15 | **Overheating Type T1-T2** |
| **TFO12** | 5167 | 243.3 | 4.4 | 4.5 | 3.0 | 6.0 | 1.1 | 262 | 0.00 | **normal** |
| **TFO13** | 3479 | 1086.1 | 26.5 | 17.6 | 2.5 | 13.6 | 0.9 | 1147 | 0.00 | **Overheating** |
| **TFO14** | 217 | 42.9 | 5.8 | 5.1 | 1.5 | 0.7 | <0.1 | 56 | 0.40 | **Normal** |
| **TFO15** | 5559 | 456.4 | 10.6 | 4.4 | 1.4 | 8.6 | <0.1 | 481 | 0.00 | **Overheating** |
| **TFO16** | 1969 | 569.0 | 33.9 | 8.9 | 1.0 | 0.6 | 0.6 | 614 | 0.00 | **normal** |
| **TFO17** | 1030 | 191.9 | 8.6 | 18.3 | 32.6 | 1.8 | <0.1 | 253 | 0.75 | **Overheating** |
| **TFO18** | 1393 | 156.3 | 11.0 | 25.9 | 38.0 | 1.4 | <0.1 | 233 | 0.00 | **Normal** |
| **TFO19** | 8216 | 299.1 | 14.3 | 3.5 | 1.2 | 32.8 | 21.2 | 372 | 0.00 | **Discharge, type D2** |
| **TFO20** | 9014 | 437.8 | 59.0 | 14.6 | 55.7 | 127.5 | 0.9 | 696 | 0.19 | **Overheating** |
| **TFO21** | 5179 | 396.9 | 9.1 | 4.6 | 1.3 | 3.8 | <0.1 | 416 | 0.00 | **Overheating** |
| **TFO22** | 3530 | 231.0 | 7.5 | 3.6 | 1.3 | 3.3 | <0.1 | 247 | 0.00 | **Overheating** |
| **TFO23** | 671 | 139.4 | 7.2 | 1.1 | 0.2 | 0.3 | <0.1 | 148 | 0.00 | **Overheating** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **TFO24** | 2998 | 386.9 | 265.6 | 10.7 | 33.5 | 6.7 | 0.3 | 704 | 0.00 | **Overheating** |
| **TFO25** | 1379 | 449.7 | 23.1 | 4.2 | 1.6 | 0.9 | <0.1 | 480 | 0.00 | **Normal** |

### 4.2 METHODOLOGIES USED

All transformers in service generate gases to some extent, and the fundamental problem with AGD is being able to distinguish between normal and abnormal states. The personnel who interpret AGD results are usually experts in the field, so they use their previous experience to interpret the data. There are many methods for interpreting the excess gases produced. These include the IEC, Doernenburg and Rogers ratio techniques, graphical methods such as the Duval triangle, and the IEEE concentration method [28]. Each of these techniques has its own advantages and limitations. The accuracy of these techniques depends on the expertise of the person performing the analysis [29] [30].

#### 4.2.1 REPORTING TECHNIQUE

The ratio technique uses the concentration ratios of the various key gases, as shown in Table 4.

*Table 4. The different gas ratios*

| **Different gas ratios** | **R1 _** | **R 2** | **R 3** | **R 4** | **R 5** | **R 6** |
|---|---|---|---|---|---|---|
| | $R_1 = \frac{CH_4}{H_2}$ | $R_2 = \frac{C_2H_2}{C_2H_4}$ | $R_3 = \frac{C_2H_2}{CH_4}$ | $R_4 = \frac{C_2H_6}{C_2H_2}$ | $R_5 = \frac{C_2H_6}{CH_4}$ | $R_6 = \frac{C_2H_4}{C_2H_6}$ |

We can cite the following techniques:

##### 4.2.1.1 THE ROGERS METHOD

Rogers has proposed different codes (0,1,2,5) for the ratios $R_1$ , $R_2$, $R_5$, $R_6$ [31] [12] [32]: Each code corresponds to a range of variation of each ratio. The ranges of the different ratios and their codes are shown in Table 5.

*Table 5. Ranges of ratios and their code according to Rogers [31]*

| Gas ratio | Ranges | Codes |
|---|---|---|
| $R_1$ | $\leq 0{,}1$<br>$> 0{,}1 < 1$<br>$\geq 1 < 3$<br>$\geq 3$ | 5<br>0<br>1<br>2 |
| $R_2$ | $< 1$<br>$\geq 1$ | 0<br>1 |
| $R_5$ | $< 1$<br>$\geq 1 < 3$<br>$\geq 3$ | 0<br>1<br>2 |
| $R_6$ | $< 0{,}5$<br>$\geq 0{,}5 < 3$<br>$\geq 3$ | 0<br>1<br>2 |

The last column of Table 4 represents the code for the four ratios for each of their range of variation. The combination of codes for all four ratios can be linked to a diagnostic interpretation as shown in [22].

##### 4.2.1.2 THE IEC 60599 METHOD

This method is based on the same gas ratios used in Rogers' method. Using three fundamental gas ratios: $R_1$, $R_2$, $R_6$, the codes for the different gas ratios are given in Table 6. The types of defects related to the IEC method are presented in [22].

*Table 6. Gas report codes relating to the IEC method [31]*

| The intervals for the codes | Default characteristic gas ratios | | |
|---|---|---|---|
| | $R_2 = \frac{C_2H_2}{C_2H_4}$ | $R_1 = \frac{CH_4}{H_2}$ | $R_6 = \frac{C_2H_4}{C_2H_6}$ |
| $< 0,1$ | 0 | 1 | 0 |
| $0,1 - 1$ | 1 | 0 | 0 |
| $1 - 3$ | 1 | 2 | 1 |
| $> 3$ | 2 | 2 | 2 |

#### 4.2.1.3 DOERNENBURG'S METHOD

The Doernenburg method uses four calculated gas ratios to indicate a particular fault type from three possible fault types. This procedure requires high gas levels for the diagnosis to be valid [30] [32].

The four ratios and their diagnostic values are shown in Table 7. The method requires the significant presence of gas concentration levels in order for the diagnosis to be valid [31], and these have since been adjusted and adopted by IEEE. Once the determination of gas levels is sufficiently within acceptable limits [33], the ratios $R_1$, $R_2$, $R_3$ and $R_4$ are calculated. And Table 7 gives the limit values for the ratios of dissolved gases in transformer oil [32].

*Table 7. Key gas ratios according to Doernenburg*

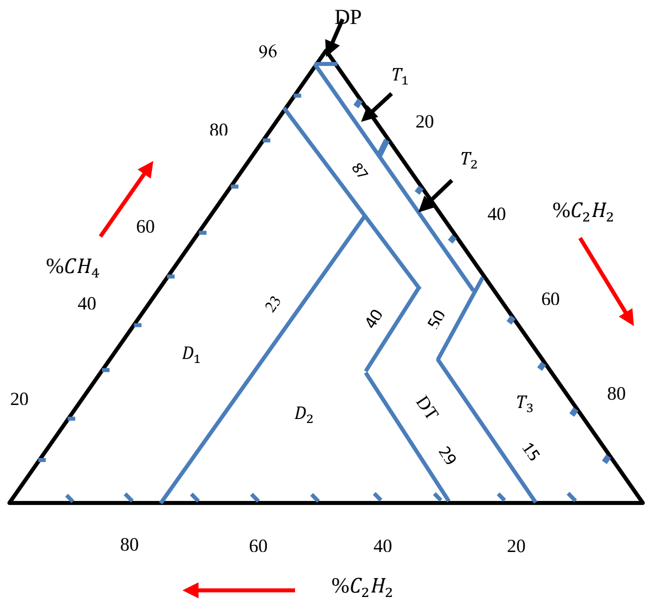
| Suggested fault diagnosis | Oil Gas Space Extract | | | |
|---|---|---|---|---|
| | $R_1$ | $R_2$ | $R_3$ | $R_4$ |
| **Thermal decomposition** | $> 1.0$<br>$> 1.0$ | $< 0,75$<br>$< 1,0$ | $< 0,3$<br>$< 0,1$ | $> 0,4$<br>$> 0,2$ |
| **Corona effect (low energy DP)** | $< 0,1$<br>$< 0,01$ | Not signified | $< 0,3$<br>$< 0,1$ | $> 0,4$<br>$> 0,2$ |
| **ARC (high energy DP)** | $> 0,1$<br>$> 0,01$<br>$< 1,0$<br>$< 0,1$ | $> 0,75$<br>$> 1.0$ | $> 0,3$<br>$> 0,1$ | $< 0,4$<br>$< 0,2$ |

### 4.2.2 IEEE STANDARD METHOD C57.104

This method is called Total Dissolved Combustible Gas (TDCG). IEEE standard C57.104 takes all combustible gases into consideration. However, in applying it, it is not easy to determine the normal operating state of a transformer, and whether it has any previous history of dissolved gas. In general, this technique considers three types of fault: thermal, low-energy electrical and high-energy. In addition, Total Combustible Dissolved Gas Concentration (TDCG), concentration thresholds for four different conditions and a ratio technique (Key Gas) are suggested. The ratios used for key gases are similar to those in IEC 60599. Transformer condition is determined by finding the highest level for individual gases or for all combustible gases. Concentration limits for gases dissolved in oil according to IEEE criteria are given in [34] [35]. Detailed procedures are described in IEEE standard C57.104-2008 [34] [36] [37].

### 4.2.3 DUVAL GRAPHICAL REPRESENTATIONS

This diagnostic method is based on the calculation of the relative percentage of three gases. It uses only three hydrocarbon gases ($CH_4$, $C_2H_4$ and $C_2H_2$) [39]. These three gases correspond to the increasing levels of energy required to produce gases in transformers in service [31] [38]. The triangle method is shown in figure 1. The different fault zones mentioned below in Figure 5 (PD, $D_1$, $D_2$, $T_1$, $T_2$ or $T_3$), an intermediate DT zone has been assigned to mixtures of electrical and thermal faults in the transformer [32] [39].




**Legend:**

PD = Partial discharge

$T_1$ thermal fault less than 300°C

$T_2$ = thermal fault between 300°C and 700°C

$T_3$ = thermal fault greater than 700°C

$D_1$ = low energy discharge (sparking)

$D_2$ = high energy discharge (Arc)

DT = mix of thermal and electrical faults

*Fig. 1. Diagram of Duval's triangle [40]*

This method consists in calculating percentage concentrations in (ppm) of the three gases $CH_4$, $C_2H_4$, $C_2H_2$ relative to the total ($CH_4$+$C_2H_4$+$C_2H_2$). Detailed procedures are described in IEEE standard C57.104-2008 [34].

## 5 RESULTS AND DISCUSSIONS

To test the conventional methods of Duval's triangle, Rogers' ratios, IEC 60599 and Doerneburg and the method of IEEE standard C57.104, we used a database of 25 samples of oils from the transformer park in the northern part of Abidjan of the Compagnie Ivoirienne d'Electricité (CIE). Tables 8 and 9 illustrate the diagnostic results based on dissolved gas analysis in 25 mineral oil samples by defect type: DP, $D_1$, $D_2$, $T_1$ & $T_2$, and, $T_3$.

*Table 8. Concentration of gases dissolved in the oil and the results following the 5 methods of interpretation*

| Samples | Different dissolved gases | | | | | Recorded faults | Diagnosis according to | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | | IEEE | IEC | Doernenburg | Rogers | Duval's T. |
| TFO1 | 151.9 | 9.6 | 44.9 | 6.6 | 0.2 | DP | N | DP | DP | ND | T2 |
| TFO2 | 257.3 | 11.2 | 41.5 | 7 | 0.3 | DP | N | DP | DP | ND | T2 |
| TFO3 | 180.2 | 210.1 | 680.8 | 16.9 | <0.1 | DT | ND | DT,T2 | ND | DT, T1 | T1 |
| TFO4 | 5.5 | 0.9 | 0.1 | 0.1 | 0.1 | DT | N | DE,D1 | ND | DE, D2 | DT |
| TFO5 | 26.1 | 12.0 | 25.6 | 2.4 | 0.2 | DT | N | N | ND | DT, T1 | T1 |
| TFO6 | 6.7 | 4.3 | 2.6 | 29.5 | 0.2 | DT | N | ND | ND | ND | T3 |
| TFO7 | 16 | 6.2 | 1 | 2.2 | <0.1 | DT | DT | ND | ND | DT | T2 |
| TFO8 | 19.8 | 23 | 54.3 | 2.8 | <0.1 | DT | N | DT, T2 | ND | DT, T1 | T1 |
| TFO9 | 9.0 | 6.0 | 1.1 | 3.2 | <0.1 | DT | DT | ND | ND | DT | T2 |
| TFO10 | 200.5 | 7.5 | 31.1 | 5.1 | 0.4 | DT | N | DP | DP | ND | T2 |
| TFO11 | 164.6 | 83.9 | 329.4 | 86.3 | 4.3 | DT | ND | N | DP | DT, T2 | T3 |
| TFO12 | 4.4 | 4.5 | 3.0 | 6.0 | 1.1 | N | DT | DE, D1 | DT | DT | T3 |
| TFO13 | 26.5 | 17.6 | 2.5 | 13.6 | 0.9 | DT | DT | ND | ND | ND | T2 |
| TFO14 | 5.8 | 5.1 | 1.5 | 0.7 | <0.1 | N | N | N | ND | N | T1 |
| TFO15 | 10.6 | 4.4 | 1.4 | 8.6 | <0.1 | DT | DT | ND | ND | ND | T3 |
| TFO16 | 33.9 | 8.9 | 1.0 | 0.6 | 0.6 | N | DT | ND | ND | DE, D1 | DT |
| TFO17 | 8.6 | 18.3 | 32.6 | 1.8 | <0.1 | DT | N | DT, T1 | ND | DT, T1 | T1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **TFO18** | 11.0 | 25.9 | 38.0 | 1.4 | <0.1 | **N** | **N** | **DT, T1** | **ND** | **DT, T1** | **T1** |
| **TFO19** | 14.3 | 3.5 | 1.2 | 32.8 | 21.2 | **D2** | **N** | **DE, D1** | **ND** | **DE, D2** | **D2** |
| **TFO20** | 59.0 | 14.6 | 55.7 | 127.5 | 0.9 | **DT** | **ND** | **DT, T1** | **ND** | **ND** | **T3** |
| **TFO21** | 9.1 | 4.6 | 1.3 | 3.8 | <0.1 | **DT** | **DT** | **DT, T1** | **ND** | **DT** | **T2** |
| **TFO22** | 7.5 | 3.6 | 1.3 | 3.3 | <0.1 | **DT** | **DT** | **DT, T1** | **ND** | **DT** | **T2** |
| **TFO23** | 7.2 | 1.1 | 0.2 | 0.3 | <0.1 | **DT** | **DT** | **DT ,T1** | **ND** | **DT** | **T2** |
| **TFO24** | 265.6 | 10.7 | 33.5 | 6.7 | 0.3 | **DT** | **N** | **DP** | **ND** | **ND** | **T2** |
| **TFO25** | 23.1 | 4.2 | 1.6 | 0.9 | <0.1 | **N** | **DT** | **N** | **ND** | **N** | **T1** |

***Table 9. Diagnostic result of transformer oil samples according to the different criteria: comparison.***

| **Type** | | **E0** | **E1** | **E2** | **E3** | **E4** | **E5** | **E6** | **E7** | **E8** | **E9** | **E10** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Samples** | | | **5** | **17** | | | | | **1** | | **2** | **0** |
| **Defaults** | | **ND** | **N** | **OH** | | | | | **D** | | **DP** | **DT** |
| | | | | **TO** | **CT** | **T1** | **T2** | **T3** | **D1** | **D2** | | |
| **Methods** | **Doernenburg** | 20 | 0 | 0 | 0 | 1 | | | 0 | | 4 | 0 |
| | **Rogers** | 8 | 2 | 0 | 0 | 5 | 1 | 0 | 1 | 2 | 0 | 6 |
| | **Duval's T.** | 0 | 0 | 0 | 0 | 7 | 10 | 4 | 1 | 1 | 0 | 2 |
| | **IEEE** | 3 | 12 | 3 | 9 | 0 | 10 | 0 | 0 | 0 | 0 | 0 |
| | **IEC** | 6 | 4 | 0 | 0 | 6 | 2 | 0 | 3 | 0 | 4 | 0 |

In the interpretation that can help the CIE to make a choice or a correct diagnosis, we have determined the success rate of correct cases. We can see that the Duval and Rogers triangle diagnostic criteria have the highest success rate (over 50%), followed by the IEC and IEEE criteria, and the lowest rate for the Doernenburg criterion. The error rate is calculated by taking into account the fact that during diagnosis, there were many cases of indecision (ND), which we removed from the number of samples to be diagnosed as shown in the equation. Table 10 summarizes the different diagnostic success and error rates (equation1) for the 25 samples.

$$\text{Error in } \% = \frac{\text{NED}-(\text{NCR}+\text{NND})}{\text{NED}} \quad (1)$$

With:

NED: Number of Samples to be Diagnosed
NCR: Number of Successful Cases
NND: Number of No-Decisions

Using this formula, we see that the IEEE method has the highest error rate at 52% and the Doernenburg method the lowest. This is justified by the fact that this method has the highest indecision cases

***Table 10. Rate of correct analysis by the different criteria***

| **Diagnosis according to** | **Number of correct cases out of the 25 samples** | **Number of incorrect cases out of the 25 samples** | **Percentage % of correct cases** | **Error rate in %** |
|---|---|---|---|---|
| **Doernenburg** | 2 | 3 | **8** | **12** |
| **Rogers** | 13 | 4 | **52** | **16** |
| **Duval's Triangle** | 18 | 7 | **72** | **28** |
| **IEEE (key gas)** | 9 | 13 | **36** | **52** |
| **IEC** | 12 | 7 | **48** | **28** |

We then classified the main faults as electrical discharges (ED), partial discharges (PD) and overheating (DT) [42], as well as the case of transformers in normal condition, in order to appreciate the different diagnostic methods (interpretation). We have considered faults combining thermal and electrical faults to be thermal faults. It should be noted that not even the expert differentiated between TC, TO, $T_1$, $T_2$ and $T_3$ thermal faults. This gives us Table 11. We note that all the interpretation criteria were able to diagnose the case of overheating except Doernenburg. For partial discharges, only the IEC and Doernenburg methods have a good 100% diagnosis, while the

IEEE, Rogers and Duval criteria did not detect this fault. When we look at electrical faults, apart from the Doernenburg and IEEE methods, which have a poor diagnosis of 0%, the Rogers, IEC and Duval triangle methods have a better prognosis of 100%.

*Table 11. The main "Det" defects detected by the different interpretation criteria*

| Diagnosis according to | Different main faults detected | | | |
|---|---|---|---|---|
| | Regular (N) | Electric discharge (ED) | Partial Discharge (PD) | Overheating (DT) |
| Doernenburg | 0 | 0 | 2 | 0 |
| Rogers | 2 | 1 | 0 | 10 |
| Duval's Triangle | 0 | 1 | 0 | 17 |
| IEEE (key gas) | 2 | 0 | 0 | 7 |
| IEC | 2 | 1 | 2 | 7 |

In order to make a good comparison of the different methods, we calculated the percentage (equation 2) $P_{DFi}$ of successful prediction of a particular defect type DFi from the relationship: The final success rate, corresponding to the percentage of cases identical to the inspection, of the 25 samples is presented for each method in Table 12

$$P_{DFi} = \frac{R_{DFi}}{\text{nombre de cas de défautes } DF_i} \quad (2)$$

*Table 12. Rate of the various defects detected by the various methods*

| Diagnosis according to | Different faults DFi | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Normal | | | Electric discharge | | | Partial discharge | | | Thermal fault | | |
| Actual defects | 5 | | | 1 | | | 2 | | | 17 | | |
| | Det | $R_{DFi}$ | $P_{DFi}$ | Det | $R_{DFi}$ | $P_{DFi}$ | Det | $R_{DFi}$ | $P_{DFi}$ | Det | $R_{DFi}$ | $P_{DFi}$ |
| Doernenburg | 0 | 0 | **0** | 0 | 0 | **0** | 4 | 2 | **100** | 1 | 0 | **0** |
| Rogers | 2 | 2 | **40** | 3 | 1 | **100** | 0 | 0 | **0** | 12 | 10 | **58.82** |
| Duval's Triangle | 0 | 0 | **0** | 2 | 1 | **100** | 0 | 0 | **0** | 23 | 17 | **100** |
| IEEE (key gas) | 12 | 2 | **40** | 0 | 0 | **0** | 0 | 0 | **0** | 10 | 7 | **41.18** |
| IEC | 4 | 2 | **40** | 3 | 1 | **100** | 4 | 2 | **100** | 8 | 7 | **41.18** |

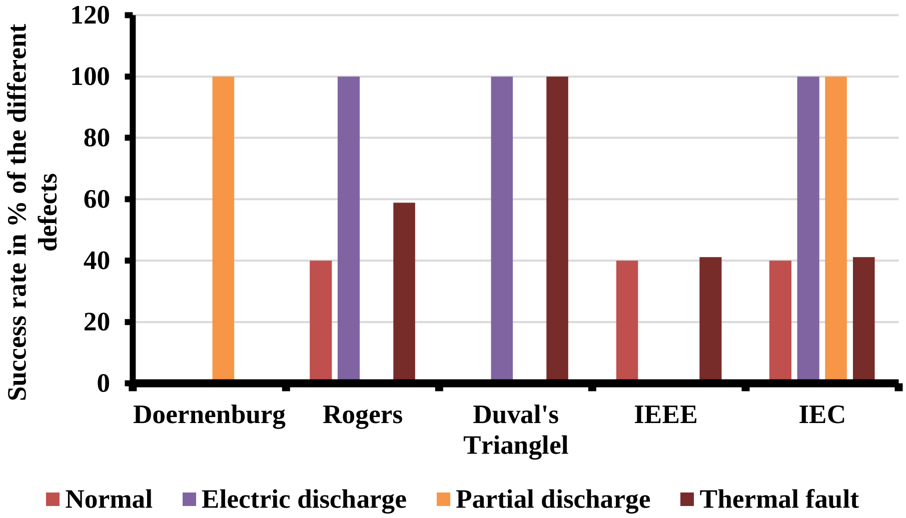



*Fig. 2. Defect success rates using conventional methods*

Table 12 and Figure 2 give us the different success rates in detecting the different defect cases, confirming what we said in the previous paragraph. We have thus calculated the consistency of the different methods. Table 13 and Figure 3 show the different results.

Here, we can see that the IEC method is the most consistent in terms of fault diagnosis. The IEEE method, on the other hand, is the least consistent. Proof that it has succeeded in diagnosing all faults.

- N: is the number of faults for each type of real faults
- $R_{DFi}$: the number of successful predictions for each type of fault
- $P_{DFi}$ = percentage of successful prediction of a particular fault type$DF_i$

The consistency of the methods is given by the equation 3:

$$\text{Consistency} = \frac{\sum_{i=1}^{n} P_{DFi}}{N} \quad (3)$$

*Table 13. Consistency of the different methods*

| Diagnosis according to | Normal | Electric discharge | Partial discharge | Thermal fault | Consistency of the method in % |
|---|---|---|---|---|---|
| **Doernenburg** | 0 | 0 | 100 | 0 | **25** |
| **Rogers** | 40 | 100 | 0 | 58.82 | **49.71** |
| **Duval's Triangle** | 0 | 100 | 0 | 100 | **50** |
| **IEEE** | 40 | 0 | 0 | 41.18 | **20.30** |
| **IEC** | 40 | 100 | 100 | 41.18 | **70.30** |

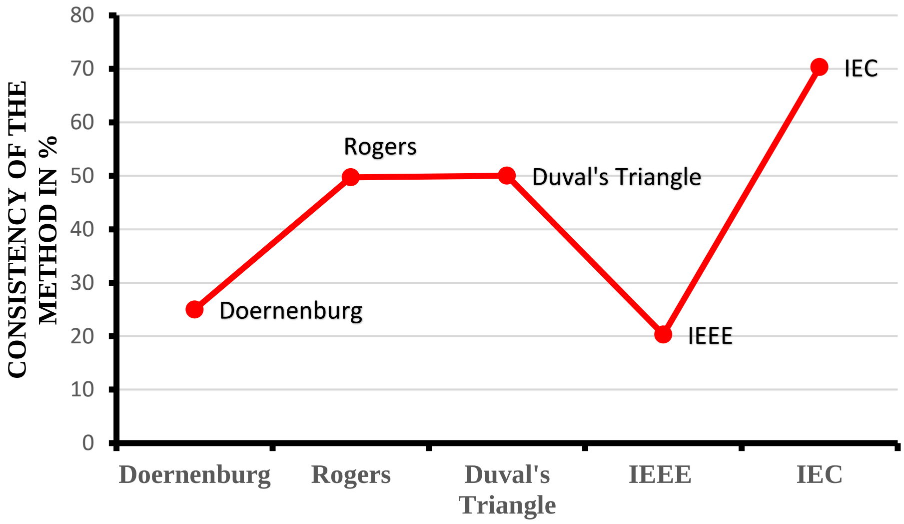



*Fig. 3. Diagram representing the consistency of the different diagnostic criteria*

## 6 Conclusion

This research work deals with the diagnosis of power transformers using conventional methods of: Doernenburg, Rogers, IEEE (TDCG), IEC 60599 and the Duval triangle. We compared diagnostic results using these five (5) methods. The results show that the interpretation method following the Duval triangle criterion made the highest correct diagnosis rate of 72%, but could not identify either the normal case or the partial defects. Comparatively, the IEC 60599 criterion succeeded in identifying all cases of faults and therefore was the most consistent with a rate of almost 71%. The Doernenburg criterion had the lowest diagnosis rate with especially many "unidentified" cases. The 5 conventional methods are not 100% consistent and they do not necessarily lead to the same conclusion for the same oil sample. In addition, a significant number of AGD results fall outside the proposed codes for interpretive techniques. The limitations of these methods require them to be combined with more efficient diagnostic systems such as artificial intelligence (AI) techniques. Combining conventional methods with AI techniques will be the subject of the next article.

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