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RESEARCH ARTICLE

DIAGNOSIS OF POWER TRANSFORMERS INSTALLED IN THE ABIDJAN SOUTH AREA IN CÔTE D'IVOIRE USING DATABASES CONSISTING OF GAS ANALYSIS RESULTS DISSOLVED IN INSULATING OIL

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Abstract

The transformer is the most important piece of equipment in the electric power system used to transmit and distribute electricity. The oil/paper mixed insulation system is one of the essential parts due to the various defects that can be produced in this part. In general, the insulating oil contains about 70% of the information on the state of health of the power transformer. We received from the national electricity company the measurement data (Analysis of dissolved gases: AGD) made on transformers in the region of Abidjan Sud which we analyzed in order to detect defects. AGD is an effective technique for diagnosing and ensuring early detection of incipient faults in transformers and making decisions to reduce unplanned failures. The objectives of this research work were to give, from data analysis, the state of health of the transformers installed in the region of Abidjan Sud and to propose to the national electricity company as well as to the various Ivorian companies the most appropriate interpretation method for AGD. The interpretation methods used are: Doernenburg, Rogers, Duval, IEEE and IEC. The study on the different transformers made it possible to show that the IEC criterion had the best rate of correct analysis, while that of Doernenburg had the lowest rate. The state of health of the various processors was also highlighted.

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Introduction:-

Electricity is an integral part of our life. Without electricity life stops. This dependence imposes a permanent service on electricity production and transmission companies, especially with regard to strategic infrastructures. A power interruption can cause irreparable damage to them. Interruptions are usually caused by outdated electrical equipment, especially transformers. The power transformer is the most critical element in the power transmission system [1][2] . Reliability in its operation therefore plays an important role in the stability and availability of the entire electrical network [3] . Its unavailability not only affects the availability of electrical energy, but also leads to technical and economic penalties, which are very heavy as a result (technical, financial, commercial, environmental); hence the need to detect and identify latent defects at an early stage for possible preventive action [4][5] . Paper and oil insulators are some of the important parts of the power transformer [6] . It is estimated that insulating oil contains about 70% of the diagnostic information available for transformers [7] . The reliability of any power supply system depends on the preventive diagnosis of its insulation system against faults from various

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sources (electrical, thermal, chemical, environmental, etc.) which can significantly reduce its lifespan [8][9] . Among the actions to be used to ensure the availability of transformers, maintenance actions, which consist of the implementation of preventive and corrective activities, constitute one of the essential links. The effectiveness of all this requires the application of good diagnostic methods. Dissolved gas analysis is the only way to detect a number of internal faults in transformers. Although not an exact science, evaluation and interpretation based on statistical data have been used for several decades to estimate the condition of a transformer [10] . The objective of these methods is to determine the causes of malfunction, based on observations (measurement and analysis data) and symptoms (abnormalities) observed.

Faults in transformers and interpretation techniques

Incipient faults in transformers arise from a permanent and irreversible change in the state of the transformer causing accelerated aging and deterioration of the insulation system. They can lead to permanent transformer failure.

The IEC 60599 standard classifies transformer faults detectable by gas analysis into two categories: electrical fault and thermal fault. These two main categories can be further classified into 6 types of transformer faults, depending on the magnitudes of the fault energy [11] :

1. Partial discharges (PD)
2. Low power discharge
3. High power discharge
4. Thermal faults with temperatures below 300°C
5. Thermal faults with temperatures between 300°C and 700°C
6. Thermal faults with temperatures above 700°C

Thermal fault (DT)

Referring to standards (IEC, IEEE), the decomposition of mineral oil between temperatures of 150 C° to 500 C°, produces relatively large quantities of low molecular weight gases such as hydrogen (H_2) , methane (CH_4) and ethane (C_2H_6) with smaller amounts of ethylene (C_2H_4) gas [12] . A higher fault temperature will produce a higher concentration of this gas. If there is involvement of cellulose, carbon dioxide (CO2) as well as carbon monoxide (CO) will be formed at concentrations which always depend on the intensity of the defect with the location of its location

Thermal faults result from overheated conductors, short circuits, overheated windings due to eddy currents, loose connections and insufficient cooling. Localized overheating is known as hot spots. The temperature of a hot spot on a metal surface can reach 1500°C thus causing local heating of the surrounding oil, leading to the generation of hydrocarbon gases [13][14] . Different types of fault gases will be formed in different temperature ranges; therefore, fault gases could be used to diagnose transformer fault temperature [14] .

Partial fault (DP)

A partial discharge is a very localized electrical discharge of low intensity that occurs between two separate conductors. Partial discharges appear as short-duration pulses that are often accompanied by the emission of sound, light, heat, and chemical reactions. Sources of partial discharges include voids and cracks in solid insulation, floating components such as water drops and air bubbles, and the corona effect caused by sharp edges and corners of insulation solid, windings or tank.

Usually, this type of defect is characterized by the production of hydrogen (H_2) and methane (CH_4).

Electrical fault (Arc or spark discharge) (DE)

It is generally accepted that the breakdown occurs after the streamers have propagated entirely through the electrode gap. When the energy of the dielectric breakdown is limited, it acts small arcs called "spark faults". In comparison to partial faults, sparking faults generate much more gas during the fault which can be critical for the correct operation of the transformer. Arc discharges generate very high temperatures (above 5000°C) and a large amount of gas compared to previous types, mainly acetylene and hydrogen [9][12] . This type of fault is very dangerous and, if not controlled, can cause excessive pressure in the transformer tank, which can even lead to an explosion.

The different conventional techniques for interpreting AGD measurement data

Dissolved Gas Analysis (DGA) is very popular for transformer reliability monitoring. This method is a common and effective practice in fault diagnosis because it does not require a power outage during data collection, it also has a relatively low cost and high accuracy. In service, transformers are subject to electrical stresses (partial discharges, electric arcs) and thermal stresses (overheating). Therefore, electrical insulators such as mineral oils degrade under these stresses forming gases that can be used as indicators of the type of stress and its severity [15] . Thus, the qualitative and quantitative determination of these gases is of great importance in the evaluation of the type of fault of this equipment. Based on the DGA, several interpretation criteria have been introduced to diagnose the faults that occur in the equipment (transformers) [16] . If an incipient fault is present, the concentration of each gas, the total combustible gas (TCG), and the generation rate are all greatly increased. Many DGA interpretation methods such as key gas method, Doernenburg, Rogers, Duval, IEEE and IEC (60599) have been reported. Each of these techniques has its own advantages and limitations. These techniques do not necessarily lead to the same conclusion. Accuracy depends on the expertise of the person performing the analysis [17][18] .

Reporting technique

This technique uses the ratios of the measured quantities of gas. The ratio technique has definite advantages over other techniques because the ratios are independent of both the volume of oil and the choice of concentration units.

Table 1: - The different gas ratios.

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

Among these methods are:

The Rogers Method

This method uses the following four gas ratios [5][19][20] : These reports are exploited to generate codes based on numerical limits classified in intervals according to table 2. The combination of codes, can be related to an interpretation as it is shown in table 3.

Table 2:- Rogers ratios, intervals and codes [19].

Throttle ratio	**Intervals**	**codes**
R_1	$\leq 0{,}1$ $> 0{,}1 < 1$ $\geq 1 < 3$ ≥ 3	5 0 1 2
R_2	< 1 ≥ 1	0 1
R_5	< 1 $\geq 1 < 3$ ≥ 3	0 1 2
R_6	$< 0{,}5$ $\geq 0{,}5 < 3$ ≥ 3	0 1 2

Table 3:- Codes and faults according to the Rogers method [19].

Coded					**Interpretation**
1	0	0	0	0	normal
2	5	0	0	0	Partial discharge (PD) of low energy
3	1-2	0	0	0	Slight overheating <150°C
4	1-2	1	0	0	Slight overheating 150-200°C
5	0	1	0	0	Slight overheating 200-300°C
6	0	0	1	0	Driver overheating
7	1	0	1	0	Heating caused by current flow in the windings
8	1	0	2	0	Heating caused by the current flow in the core and the tank
9	0	0	0	1	low energy arc

10	0	0	1-2	1-2	Arc of great energy
11	0	0	2	2	Continuous spark, Arc
12	5	0	0	1-2	Partial discharge DP

The IEC 60599 method

This method of interpretation uses the Rogers method except that the ratio has been dropped since it only indicates a limited thermal fault range. Each of the six main classes of defects gives rise to a characteristic composition of gaseous hydrocarbons, which can be put in the form of an AGD interpretation table, such as that recommended below in Table 4.

Using three basic gas ratios: Table 4 applies to all types of equipment, with some differences in gas ratio limits, depending on the particular type of equipment. The codes for the different gas ratios and the classifications of faults according to the gas ratio codes are given in Tables 4 and 5 respectively [21] .

Table 4:- Gas reporting codes for the IEC method [19].

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
$\mathbf{0,1-1}$	1	0	0
$\mathbf{1-3}$	1	2	1
> 3	2	2	2

Table 5:- Types of faults relating to the IEC method [19].

No.	**Fault Types**			
1	No flaw	0	0	0
2	PD with low energy	0	1	0
3	DP with high energy	1	1	0
4	Electric shock with low energy	1	1	0
5	Electric discharge with great energy	1 or 2	0	1 or 2
6	Overheating with temperature$< 150°C$	0	0	1
7	Overheating with temperature$150°C < T < 300°C$	0	2	0
8	Overheating with temperature $300°C < T < 700°C$	0	2	1
9	Overheating with temperature$T > 700°C$	0	2	2

Doernenburg 's method

Doernenburg method uses four calculated gas ratios to indicate a particular fault type out of three possible fault types. This procedure requires high gas levels for the diagnosis to be reliable [25] [26] [27]. The four gas ratios ($R_{1,}$ $R_{2,}$ R_3 and R_4) and their diagnostic values are shown in Table 6.

Table 6: - 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 > 1.0	$< 0,75$ $< 1,0$	$< 0,3$ $< 0,1$	$> 0,4$ $> 0,2$
Corona effect (low energy DP)	$< 0,1$ $< 0,01$	Not signified	$< 0,3$ $< 0,1$	$> 0,4$ $> 0,2$
ARC (high energy DP)	$> 0,1$ $> 0,01$ $< 1,0$ $< 0,1$	$> 0,75$ > 1.0	$> 0,3$ $> 0,1$	$< 0,4$ $< 0,2$

The IEEE Method or Key Gas Method

In general, this technique considers three types of faults: thermal, electrical low energy and high energy. In addition, the total dissolved combustible gas concentration (TDCG: does not include CO_2, which is not a combustible gas), concentration thresholds for four different conditions and a Key Gas technique are shown. 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. Table 7 gives the concentration limits of gases dissolved in oil according to the IEEE criterion.

Table 7:- Concentration limits of gases dissolved in oil according to IEEE [22].

State	Concentration of key gases in ppm							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	**CO**	**CO_2**	**TDCG**
Condition 1	100	120	35	50	65	350	2500	720
Condition 2	101-700	121-400	36-50	51-100	66-100	351-570	2501-4000	721-1920
Condition 3	701-1800	401-1000	51-80	101-200	101-150	571-1400	4001-10000	1921-4630
Condition 4	>1800	>1000	>80	>200	>150	>1400	>10000	>4630

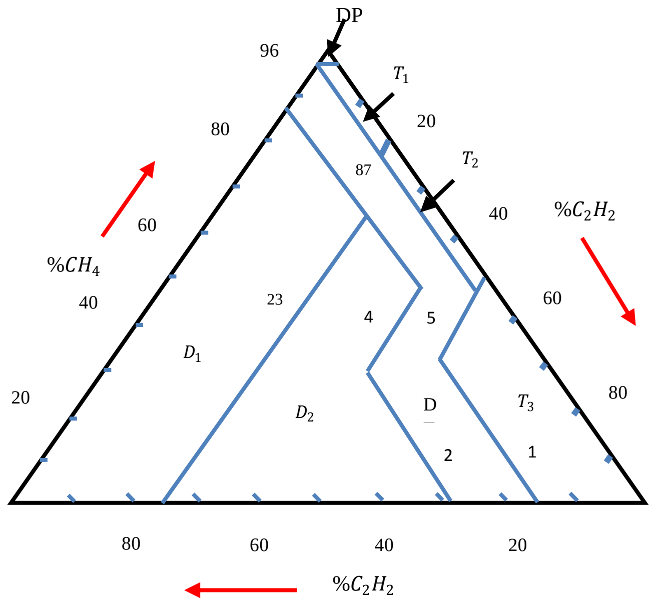
Detailed procedures are described in IEEE standard C57.104-2008 [21].[23] . The key gas method can be considered as a modification of the TDCG method**.** This technique associates each individual gas with a probable fault. These gases are called "key gases". Table 8indicates these and the relative proportions for the four major types of defect [19] .

Table 8:- Diagnostic criteria by the key gas method.

Defaults	**gas keys**	**Gases detected**	**Gas quantity in %**
Electric arcs	Acetylene (C_2H_2)	Formation of large amounts of hydrogen and acetylene, with small amounts of methane and ethylene. There may also be formation of CO and CO_2 if there is cellulose at the location of the defect.	H_2: 60% C_2H_2: 30%
Partial discharges (corona effect)	Hydrogen H_2	Low-energy landfills produce hydrogen and methane, with small amounts of ethane and ethylene. Comparable amounts of CO and CO_2 can come from landfills in cellulose	H_2: 85% CH_4: 13%
Oil overheating	Ethylene (C_2H_4)	The gases produced are ethylene and methane, with small amounts of hydrogen and ethane. Traces of acetylene can be produced if the overheating is severe or if an electrical contact intervenes in the fault.	C_2H_4: 63% C_2H_6: 20%
Cellulose overheating	Carbon monoxide (CO)	Formation of large quantities of CO and CO_2. If the defect occurs in an impregnated structure. Methane and ethylene. are also formed	CO: 92%

Graphic representations of Duval

Graphical representations of gas ratios are handy for visually tracking the progress of faults. This diagnostic method is based on the calculation of the relative percentage of three gases. Each corner of the triangle represents 100% of one gas and 0% of other gases [5] . The Duval Triangle was first developed in 1974. It uses only three hydrocarbon gases (CH_4, C_2H_4 and C_2H_2). These three gases correspond to the increasing levels of energy required to produce gases in in-service transformers [24] . The triangle method is shown in figure 1. The abbreviations of the different faults (PD, D_1, D_2, T_1, T_2 or T_3), an intermediate DT zone has been assigned to the mixtures of electrical and thermal faults in the transformer are mentioned there [25] .



Legend:

PD = partial discharge

T1 = thermal fault less than 300°C

T2 = thermal fault between 300°C and 700°C

T3 = thermal fault greater than 700°C

D1 = low energy discharge (sparking)

D2 = high energy discharge (Arc)

DT = mixture of thermal and electrical faults

Figure 1:- Diagram of Duval's triangle [26].

It does not use Hydrogen, so it is to be expected that this method will have a reduced sensitivity for faults classified as "Partial Discharge", this observation can be illustrated by the space reserved for the diagnosis of a condition partial discharge on Duval's triangle. This method consists of calculating percentage concentrations in (ppm) of the three gases CH_4, C_2H_4, C_2H_2 relatives to their total sum (x+ y+ z). The equations defining the different concentrations are written as follows:

$$\%\ CH_4 = \frac{100.x}{x+y+z}\ ;(1)$$
$$\%\ C_2H_4 = \frac{100.y}{x+y+z}\ ;(2)$$
$$\%C_2H_2 = \frac{100.z}{x+y+z}(3)$$

where $x = [CH_4]$, $y = [C_2H_4]$; $z = [C_2H_2]$represent the values of the concentrations of gases dissolved in the oil in ppm [26] .

These percentages ($\%CH_4$, $\%C_2H_4$, $\%C_2H_2$) will be plotted on the Duval triangle. Lines drawn through the triangle for each gas parallel to the hatching shown on each side of the triangle, provide only one point in the triangle [25] .

Data on Abidjan South processors

The data used in this research work come from the results of the AGD on the oil samples taken from 25 power transformers in service on the electrical network. These 25 transformers are operated by the CompagnieIvoirienned'Electricité (CIE) in Côte d'Ivoire. Figure 2 shows an example of a power transformer installed in the municipality of Vridi, the characteristics of which are: Voltage: 90/16.5 kV; Power: 40MVA; Manufacturer: IEL; Installed: 2014. Table 9 presents the transformers and their respective characteristics.

Figure 2:- 90/16.5 kV transformer; 40 MVA installed in Vridi.

The concentrations of the main dissolved gases of the samples taken from the CIE transformers, in ppm and the actual fault of each sample used as a database are presented in the following table 10 [27] . It should be noted that these gases are obtained by gas chromatography and the defects are interpreted by experts. The various key gases dissolved in power transformer oil are: methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2) hydrogen (H_2), carbon monoxide and dioxide (CO, CO_2) [28] .

Table 9:- Characteristics of transformers in Abidjan Sud.

Transformers	Features			Year of commissioning
	Voltage kV	Power MVA	Maker	
TFO1	90/16.5	40	IEL	2014
TFO2	225/90	100		2016
TFO3	90/16.5	36	JS	nineteen eighty one
TFO4	90/16.5	36	EFACEC-Portugal	2011
TFO5	225/90	70	JS	1979
TFO6	90/16.5	50	Tironi	1999
TFO7	90/16.5	40	Tironi	1999
TFO8	90/16.5	36	EFACEC-Portugal	2011
TFO9	225/90	70	HOTEC	1980
TFO10	90/16.5	40	GEC-ALSTHOM	1991
TFO11	225/90	70	HOTEC	1979
TFO12	90/16.5	50	Prolec	2016
TFO13	11/220	70	Chint	2013
TFO14	90/16.5	50	Prolec	2016
TFO15	90/16.5	20	E.Marelli	1971
TFO16	220/11	70	Chint	2012
TFO17	90/16.5	50	Tironi	2000
TFO18	11/225	61	Koncar	2014
TFO19	90/16.5	50	EFACEC	2011
TFO 20	11/225	61	Koncar	2014
TFO21	90/15	36	JS	1982
TFO22	225/16.5	50	Crompton Greaves	2016
TFO23	225/90	100	Crompton Greaves	2016

TFO24	90/11	85	IEL	1984
TFO25	11/90	85	IEL	1985

For the diagnosis of the 25 transformers in the southern zone of Abidjan, we applied the 5 traditional diagnosis methods mentioned above. The concentrations and the different ratios R_1, R_2, R_3, R_4 and R_5 of gases are presented to the different methods and the results are given for each method after treatment.

Results and Discussions:-

Table 10 below gives us the results recorded according to the expert from the CompagnieIvoiriennedʼElectricité for the 25 samples of different transformer oils taken in the southern part of greater Abidjan and the different results of interpretation of the dissolved gases made using the five different conventional methods.

After analysis, the diagnosis established by the Ivorian Electricity Company made it possible to record the different types of faults encountered in power transformers in Côte d'Ivoire. The faults recorded and the interpretation from the five (5) conventional methods are recorded in Table 11 are:

1. DT thermal faults (T1 for temperatures < 150°C; T2 for temperatures between 150°C and 300°C; T3 for temperatures > 300°C);
2. DP partial discharges,
3. D electrical discharges (D1 low-energy discharge and D2 high-energy discharge);
4. NI: Unidentified fault;
5. N: transformer in normal state;
6. The notation TFOi indicates the transformer with number i.

Table 10:- 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**	**T.Duval**
TFO1	72.8	15.1	7	5.5	0.2	**N**	**N**	**N**	**N**	**N**	**T2**
TFO2	7.4	51.1	115.8	7.4	<0.1	**OH**	**N**	**OH, T2**	**NI**	**OH, T1**	**T1**
TFO3	91.2	159.5	203.2	100.3	5.4	**OH**	**OH**	**OH, T2**	**OH**	**OH, T1**	**T2**
TFO4	13.7	10.6	9.4	0.9	<0.1	**N**	**OH**	**N**	**NI**	**N**	**T1**
TFO5	146.7	231.7	934.6	216.3	<0.1	**N**	**OH**	**OH, T2**	**NI**	**OH, T2**	**T2**
TFO6	32.2	3.6	3.5	5.1	16.9	**DE**	**N**	**D1**	**DE**	**DE, D2**	**D1**
TFO7	40.7	3.8	3	3	0.1	**DP**	**N**	**NI**	**DP**	**NI**	**T2**
TFO8	13.3	37.4	60.9	1.7	<0.1	**OH**	**N**	**OH, T2**	**NI**	**OH, T1**	**T1**
TFO9	14.6	7.9	3.1	1.7	<0.1	**N**	**OH**	**DP**	**NI**	**N**	**T1**
TFO10	21.7	61	258.7	12.2	0.1	**OH**	**NI**	**OH, T2**	**OH**	**OH, T1**	**T1**
TFO11	55.7	6	2.2	2.4	<0.1	**OH**	**N**	**NI**	**NI**	**N**	**T2**
TFO12	21.6	8.6	3.1	2.9	<0.1	**N**	**DT**	**N**	**NI**	**N**	**T2**
TFO13	13.9	21.7	3.3	10.9	0.1	**OH**	**OH**	**OH, T3**	**OH**	**OH**	**T2**
TFO14	17.6	4.2	1.1	1.1	<0.1	**OH**	**OH**	**NI**	**NI**	**OH**	**T2**
TFO15	13.7	5.5	3.0	12.0	0.5	**OH**	**OH**	**NI**	**DP**	**NI**	**T3**
TFO16	174.4	35.6	4.7	1.0	<0.1	**N**	**N**	**N**	**NI**	**N**	**DP**
TFO17	7.0	5.1	4.4	3.2	<0.1	**N**	**N**	**N**	**NI**	**N**	**T2**
TFO18	1.0	1.5	0.2	0.4	<0.1	**OH**	**OH**	**OH, T2**	**NI**	**NI**	**T2**
TFO19	218.2	17.2	10.6	18.7	<0.1	**N**	**N**	**N**	**NI**	**OH, T2**	**T1**
TFO20	1.9	4.8	1.1	1.1	<0.1	**OH**	**OH**	**OH,**	**NI**	**DT**	**T1**

								T2			
TFO21	90.7	75.1	60.7	190.3	6.9	**OH**	**NI**	**NI**	**NI**	**NI**	**T3**
TFO22	9.4	1.3	<0.1	0.3	<0.1	**N**	**OH**	**NI**	**NI**	**NI**	**T1**
TFO23	12.2	55.5	122.4	4.4	<0.1	**OH**	**NI**	**OH, T1**	**NI**	**OH, T1**	**T1**
TFO24	228.3	41.3	36.5	4.5	0.4	**N**	**DP**	**N**	**NI**	**N**	**T1**
TFO25	1208.9	109	74.1	38.1	2.3	**OH**	**OH**	**N**	**NI**	**DP**	**T2**

At the outputs of the interpretation made by the various conventional diagnostic methods, we have the diagnostic results in table 10 which we will exploit by comparing the various interpretation criteria. We thus have: for overheating in oil (TO) and overheating in paper (TC), out of the 5 criteria, only the IEEE criterion (key gases) succeeded in detecting these types of default; for overheating T1, T2 and T3 (faults at variable temperature between 150°C and more than 700°C), we see that the IEEE criterion could not detect a single case, while the Duval triangle criteria and the IEC criterion passed everything. The Rogers criterion did not detect overheating at T3 (T3>700°C). Doernenburg 's criterion for overheating, he made a diagnosis of 3 out of 13 possible. As for electric discharge faults, the criteria of Doernenburg, Rogers, Duval's triangle and IEC succeeded in making the diagnosis while the criterion of IEEE could not. For partial discharge (PD) diagnosis, all methods passed the test. We note that Duval's triangle is the only interpretation criterion that succeeded in making a diagnosis without having a case of "NI: Not Identified" and that the five criteria often do not give the same diagnoses. This is confirmed in [12].[29][30] . On the other hand, the Doernenburg method gives a fairly large number of "NI: Not Identified" cases, which is 18 out of 25 samples to be diagnosed. Also, it should be noted that Duval's triangle cannot diagnose a transformer in the normal state, and therefore a useful method for transformers which only show faults. What we can still notice is that, the methods according to the IEC and Rogers succeeded in detecting all the cases of faults including the cases of normal transformers. Table 11 gives us a summary of the diagnosis of the 25 transformers.

Table 11:- Diagnostic result of transformer oil samples according to the different criteria: comparison.

Kind		**E0**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
Samples			10			13			1		1	0
Defaults		**NI**	**N**			**OH**			**D**		**PD**	**DT**
				TO	**TC**	**T1**	**T2**	**T3**	**D1**	**D2**		
Methods	**Doernenburg**	18	1	0	0		3		1		6	0
	Rogers	6	7	0	0	5	2	0	0	1	1	3
	Duval	0	0	0	0	10	11	2	1	0	1	0
	IEEE	3	9	3	9	0	0	0	0	0	1	0
	IEC	6	8	0	0	1	7	1	1	0	1	0

In the interpretation that can help the CIE to make a choice or make a correct diagnosis, we have determined the success rate of correct cases. We see that the diagnostic criteria according to the IEC and Rogers have the best rate, followed by the Duval triangle criteria, key gases (IEEE) and the lowest rate goes to the Doernenburg criterion and therefore a higher error rate pupil. Based on the calculation of the quadratic error, we have table 12 which gives the values of the error rates according to the different methods.

$$\text{Erroren}\,\% = \frac{\text{numberofsamplestobediagnosed} - \text{numberofsuccessfulcases}}{\text{numberofsamplestobediagnosed}} \qquad (4)$$

Table 12:- Rate of correct analysis by the different criteria.

Diagnosis according to	**Number of correct cases out of the 25 samples**	**Percentage % of correct cases**	**Error rate in %**
Doernenburg	7	28	72
Rogers	16	64	36
Duval's Triangle	14	56	44
IEEE (key gas)	11	44	56
IEC	17	68	32

We have made the classification according to the main faults which are electrical discharges (DE), partial discharges (DP) and overheating (OH) [12] and also the case of a transformer in the normal state in order to fully appreciate the different diagnostic methods (interpretation). We have considered that faults combining thermal faults and electrical faults are considered as thermal faults. It should be noted that even the expert did not make the difference between the thermal faults of the types TC, TO, T1, T2, T3. We notice that all the interpretation criteria were able to diagnose the case of overheating and that the IEEE criterion is the only one that failed to detect the electric and partial discharges. This is seen in Table 13.

Table 13:- Faults detected by the different interpretation criteria.

Diagnosis according to	**Different main faults detected**			
	Regular (N)	**Electric shock (DE)**	**Partial Discharge (PD)**	**Overheating (OH)**
Doernenburg	1	1	2	3
Rogers	7	1	1	10
Duval's Triangle	0	1	1	23
IEEE (key gas)	9	0	1	12
IEC	8	1	1	9

In order to make a good comparison of the different methods, we have calculated the percentage P_{DFi} successful prediction of a particular type of defect DF_i from the relationship:

$$P_{DFi} = \frac{R_{DFi}}{numberoffaultcasesDF_i} \quad (5)$$

Table 14:- Rate of the various defects detected by the various methods.

Diagnosis according to	**Different faults** DFi											
	Normal			**Shock**			**Partial discharge**			**Thermal fault**		
Actual defects	10			1			1			13		
	Det	R_{DFi}	P_{DFi}	Det	R_{DFi}	P_{DFi}	Det	R_{DFi}	P_{DFi}	Det	R_{DFi}	P_{DFi}
Doernenburg	1	1	**10**	1	1	**100**	2	1	**100**	3	3	**23.08**
Rogers	7	7	**70**	1	1	**100**	1	0	**0**	10	8	**61.54**
Duval's Triangle	0	0	**0**	1	1	**100**	1	0	**0**	23	13	**100**
IEEE (key gas)	9	4	**40**	0	0	**0**	1	0	**0**	12	7	**53.85**
IEC	8	8	**80**	1	1	**100**	1	0	**0**	9	8	**61.54**

Table 14 and Figure 4 give us the different success rates in detecting the different fault cases and confirm what we said in the previous paragraph. Thus we calculated the consistency of the different methods. Table 15 and Figure 5 give us the different results. There, we find that for the diagnosis of the various faults, the IEC method is the most consistent. While that of the key gases (IEEE) is the least consistent. The proof that she managed to diagnose all the faults.

- N: is the number of faults for each real fault type
- 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:

$$\text{Consistency} = \frac{\sum_{i=1}^{n} P_{DFi}}{N} \quad (6)$$

Table 15:- Consistency of the different methods.

Diagnosis according to	**Normal**	**Shock**	**Partial discharge**	**Thermal fault**	**Consistency of the method in %**
Doernenburg	10	100	100	23.08	58.27
Rogers	70	100	0	61.54	57.89
Duval's Triangle	0	100	0	100	50
IEEE (key gas)	40	0	0	53.85	23.46
IEC	80	100	0	61.54	60.39

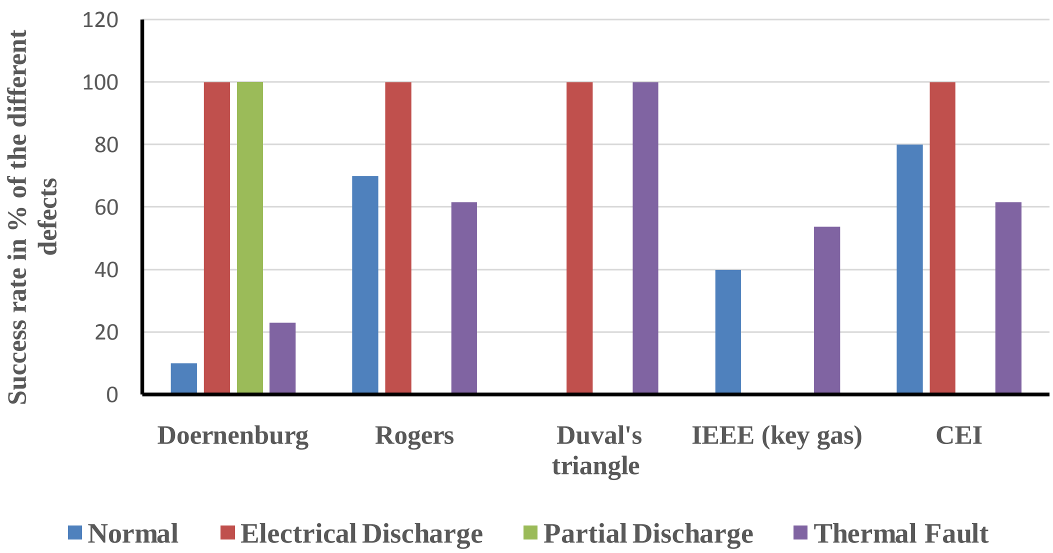


Figure 4:- Success rate of the various defects according to conventional methods.

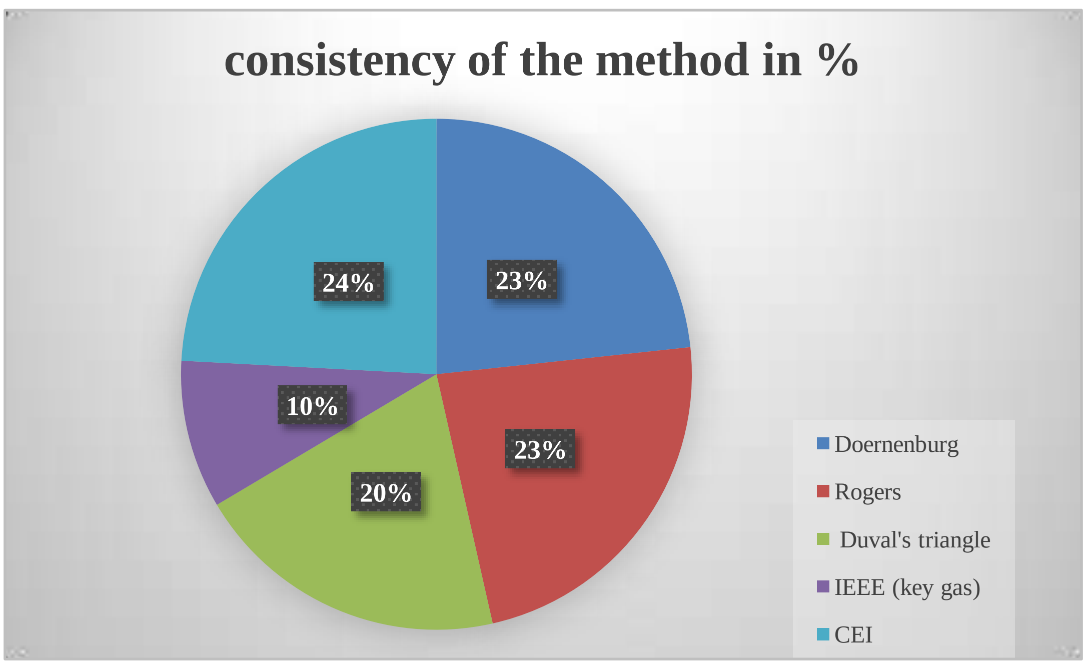


Figure 5: - Diagram representing the consistency of the various diagnostic criteria.

Conclusion:-

The work to consist in making the diagnosis of 25 transformers located in the southern part of Abidjan located in Ivory Coast in the west of Africa in the tropical part where the temperature during the year varies between 25 and 35°C. We have presented the 5 conventional criteria for interpreting the analysis of gases dissolved in transformer oil: Doernenburg, Rogers, IEEE, IEC and the Duval triangle. Given the reliability of these criteria, we used them to diagnose faults in 25 transformers whose samples were given by the CompagnieNationaled'Electricitéen Côte d'Ivoire. The results obtained indicate that the method of interpretation following the IEC criterion made the highest rate of correct diagnosis; but could not identify a few cases of defects. Compared to the Duval triangle criterion which succeeded in identifying all the default cases. The Doernenburg criterion does not make it possible to interpret faults in power transformers because with this criterion, we have 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. Additionally, a significant number of DGA results fall outside the proposed codes for ratio-based DGA interpretation techniques. With its best rate, the IEC criterion remains the most widely used in laboratories. The limitations of these methods require the use of more efficient diagnostic systems such as artificial intelligence techniques. The most used modern methods (neural networks (RNA), fuzzy logic (LF) and neuro fuzzy (NF).

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