Characterization of Faults in Power Transformers Based on Oil Chromatographic Analysis in the Coastal Zone

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Abstract. The purpose of this research work is to predict failures in power transformers based on oil chromatographic analysis and thus improve their reliability and avoid further deterioration of equipment and untimely service outages. The research is basic, descriptive, correlational level, and an experimental design. The sample consisted of 3 transformers corresponding to a company in charge of the distribution of electrical energy in the coastal area of Peru, different techniques were used such as the characteristic gas methods, from Dornemburg, from the Rogers relationships, from the total gases fuels. From the analysis of these samples, the gas content presented by the transformers was related to the faults presented by the equipment. The values found were compared with the maximum levels allowed using the key gas method. In this way, they were related to the conditions and the possible causes of breakdowns that could occur. We conclude that gas chromatography analyzes the oil that is composed of elements that make up the insulation of a transformer of many hydrocarbon bases comprised of between 16 and 22 carbon atoms, in addition to cellulose, which is a polymeric hydrocarbon that decomposes and releases gases when a thermal or electrical fault occurs. Keywords: Oil Chromatographic Analysis, Transformer Reliability, Untimely Service.

1. Introduction
It causes the interruption of energy significantly affecting the electricity supply to important cities and industries, with the consequent negative effects on the production process. The gas content in transformers can be determined by chromatographic tests performed on such equipment [1]. For many years, the oil dilute gas study method has been used as a diagnostic tool for transformers. The method is used for multiple purposes: detecting an incipient fault and monitoring the transformer. The tests carried out give us a hypothesis or explanation of a probable failure or distortion that actually occurs in the equipment. This can also be used as a strategy to monitor all existing transformers. Through the use of techniques known as: TDCG values (IEEE C57.104.2008 standards) [2], Dornenburg technique, Roger’s relationships applied to power transformers, for the analysis of the gases contained in the oil such as methane, hydrogen, ethylene, acetylene, oxygen, carbon monoxide, it will be possible to detect faults such as partial discharges, severe overloads, electric arcs, low energy arcs.

The preventive maintenance that is carried out in the electrical transformers to carry out an analysis of the state of the oil is based on the tests of insulation power factor, interfacial tension, acidity, moisture content, the insulation resistance of the oil, among others; The oil used in electrical transformers undergoes a slow degradation that, if not supervised, can release gases, the nature and quantity of which will depend on the thermal insulator and the decomposition situations of the process. The study carried
out by Carrera A. in his work on the analysis of the state of power transformers based on oil [3], had as its purpose the analysis of dielectric oil based on computer technologies, to which the data of the physical tests were fed -chemical and dilute gas data, where it was seen in the records that the data of some gases and parameters indicate changes in their results, managing to lower, this is a normal situation due to the thermo-vacuum process of the oil to separate the humidity that occurs in maintenance work.

The processes that affect the diversification of the data are: drying of the oil, occupation of the anti-explosion system, and exchange of packaging. The IEEE Std C57.104-1991 standard on which this research was based [4] indicates that its use is for mineral oils in transformers, primarily appropriate for the study of oil in the tanks, not for the oil in the box terminals (phases). The study carried out on the phases of the transformers showed an error interval in relation to the existing state of the oil. For analysis of the dielectric oil and complementary techniques by means of a preventive diagnosis of power transformers, it allows us to know the state of the transformers, once obtained the content of diluted gases in the laboratory proceeds to give an interpretation of the real state of the machine [5]. The diagnosis of transformers by the Duval Triangle method is based on the increase in the energy levels of the formation of three gases: CH₄, C₂H₆ and C₂H₂: [6].

The main functions of transformer insulating oils being to electrically separate the windings, extinguish electric arcs and eliminate heat. Maintaining the quality of the electrical fluid is essential to ensure the operation of oil-separated electrical equipment. There is a great diversity of criteria to assess the state of the oils and the constant frequency of tests. One way to maintain the reliability of the system is to analyze the loads to be applied to the transformers, as well as the type of electrical system in which the machine is located. We have, for example, the electricity distribution companies consider the maintenance of their transformers as an uneconomic task and are trained to accept a higher risk of failure.

In the industrial sector, the reliability of the system is taken into account and highly valued since a large part of its production depends on the reliability of the electrical system. In this way, by performing a more detailed inspection of the oil through preventive and predictive maintenance, they reduce the risk factor and power outages. When the oil oxidizes, degradation is generated. Safety margins fall and the risk of failure increases. Although risk assessment is difficult, predictive action consists of identifying potential impairment effects. It is looking ahead.

1.1. **Total dissolved gas analysis (TDGA)**

| Amount of combustible gases | Diagnosis |
|-----------------------------|-----------|
| 0 - 720 ppm                 | Indicates satisfactory operation. Repeat analysis every 12 months |
| 721 - 1920 ppm             | Indicates internal fault that should be investigated. Take a new sample to determine the daily amount of gas generation. |
| 1921 - 4630 ppm            | Indicates high level of cellulose and / or oil decomposition. Perform a new chromate analysis graph in the shortest period of time and calculate the daily amount of gas generation, according to these results, take the required action. |
| > 4,630 ppm.               | The solid and liquid insulations of the are decomposing rapidly, it is best to remove the transformer from service. |
Table 1. Comparative analysis gases.

| Status   | H₂  | CH₄ | C₂H₂ | C₂H₄ | C₂H₆ | CO  | CO₂ | TDCG |
|----------|-----|-----|------|------|------|-----|-----|------|
| Condition 1 | 100 | 120 | 35   | 50   | 65   | 350 | 2,500 | 720 |
| Condition 2 | 101 - 700 | 121 - 400 | 36 - 50 | 51 - 100 | 66 - 100 | 351 - 570 | 2,500 - 4,000 | 721 - 1,920 |
| Condition 3 | 701 - 1,800 | 401 - 1,000 | 51 - 80 | 101 - 200 | 101 - 1,150 | 571 - 1,400 | 4,001 - 10,000 | 1,921 - 4,630 |
| Condition 4 | > 1,800 | > 1,000 | > 80 | > 200 | > 150 | > 1,400 | > 10,000 | > 4,630 |

Norma IEEE C57.104 – 2008
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1.2. Rogers ratios for key gases
This method has a more precise scheme, as it establishes the severity of incipient fault conditions.

Table 2. Rogers relations method.

| ROGER’S RATION LIMITS |
|------------------------|
| Case | Fault diagnosis | C₂H₂/C₂H₄ | CH₄/H₂ | C₂H₄/C₂H₆ |
| 0 | Unit Normal | <0.1 | 0.1-1.0 | <1.0 |
| 1 | Low Energy density arcing | <0.1 | <0.1 | <1.0 |
| 2 | High Energy Discharge Arcing | 0.1-3.0 | 0.1-1.0 | >3.0 |
| 3 | Low Temperature | <0.1 | 0.1-1.0 | 1.0-3.0 |
| 4 | thermal faults <700 °C | <0.1 | >1.0 | 1.0-3.0 |
| 5 | Thermal faults <700 °C | <0.1 | >1.0 | >3.0 |

Source: 4th INTERNATIONAL CONFERENCE ON ELECTRICAL ENGINEERING
Comparative study of DGA interpretation methods, MA. Senoussaoui, IS. Bousmaha, MN. Brahami, and M. Brahami
It is important to take into account that if the transformer has a forced oil recirculation cooling system, this may be the cause in part of the presence of H2, CO, CH4, and C2H4 since the activity of the static discharge is very similar to the activity of partial discharges, and it may happen that up to 75% of hydrogen, 15% of carbon monoxide, 10% of Methane, and 5% of ethylene, may be due to the phenomenon of static discharge.

1.3. Doernemburg ratio limits

We can identify three types of failure: Thermal, internal arc and corona effect.

| DOERNENBURG RATIO LIMITS | CH4/H2 | C2H2/C2H4 | C2H2/CH4 | C2H6/C2H2 |
|--------------------------|--------|-----------|----------|-----------|
| Thermal Decomposition    | >0.1   | <0.75     | <0.3     | >0.4      |
| Corona                   | <0.1   | -         | <0.3     | >0.4      |
| Arcing                   | 0.1-1.0| >0.75     | >0.3     | <0.4      |

Table 3. Doernemburg ratio method.

Source: 4th International Conference on Electrical Engineering
Comparative study of DGA interpretation methods, MA. Senoussaoui, IS. Bousmaha, MN. Brahami, and M. Brahami

The presence of oxygen in the insulating system allows for a slow combustion that results in water and Carbon Dioxide. This generates a great variety of furan compounds that, depending on the internal conditions in the tank, can give rise to the presence of problems both in the insulating paper and in the dielectric oil and can affect the core of the transformer. [7].

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\text{Celulosa=Glucosa+H2O+CO+CO2+ Ácidos Orgánico}
\]

2. Methodology

The research carried out is experimental, for the compilation of the information formats prepared by the author were used. Likewise, for the report of the results of the chromatographic study, diagnostic rules were taken into account, such as: key gas, total fuel gases in the oil, Dornemburg relationship method, etc., the SPSS 23 computer statistic was used. The type of research is applied.

The investigation is located in the town and shows 12 power transformers in oil in the electric power distribution company in southern Peru. For the collection of reliable data from the collection of oil samples to perform the DGA consists of the following four steps: Transformer oil sample, Extraction of oil gases, Analysis of the mixture of gases obtained by means of chromatography of gases and Interpretation of the analysis according to an evaluation plan.

The location for the oil sampling was located in the radiator circuit, in the valve on the top of the cover, below the Buchholz relay. Additionally, care must be taken to ensure that the sample is not exposed to the atmosphere and that gases are not lost during sampling or while being transported to the laboratory. According to IEC Standard 60567 or ASTM Standard 3613, The gases were extracted from the oil by means of the following methods: Partial degassing Total degassing, agitation of the oil gases when discharging with another gas.

The technique of empty spaces, in which the gases are equalized between the volume of a free gas and the volume of the oil. After the extraction of the gas mixture, it enters the absorption column in a gas chromatograph, where different gases are absorbed to various degrees and reach the detector after
different periods of time. At that point, the gases are separated one by one, and their concentrations are calculated in volume of gas at standard temperature and pressure per volume of oil and expressed in parts per million.

The following materials and equipment were used for data collection: inspection forms, a syringe to store the oil, a 2-way valve, a hose, a plastic bucket, industrial cloth, and polypropylene alcohol.

Figure 1. ABB Service Handbook for Transformers 2007.

The main purpose of this stage is to obtain a representative sample of the oil contained in the transformer tank, bearing in mind that the sample must be completely clean in order not to alter the results. If the sample contains gas bubbles after using this procedure or if bubbles have formed after sampling, they should not be removed as they are part of the oil’s condition. In order to have an oil sample extraction procedure and ensure that the sample clearly reflects the condition of the transformer, certain precautions to take the oil sample, certain considerations and recommendations must be followed, which will help us obtain a representative oil sample free of bubbles and external contaminants.

• To avoid contamination with the atmosphere, the connections between the transformer valve and the syringe must be hermetically joined.
• The sampling must be done in favorable atmospheric conditions, i.e., no rain and a relative humidity of no more than 60%.
• The hose used must be as short as possible, and the rubber or plastic pipe must be impermeable to gas. The sampling point for this procedure will be at the sampling valve located in the lower part of the transformer. The sample must be taken in consideration of normal equipment work, which is important when evaluating the rate of gas production. The sample taken should be sent as quickly as possible to the laboratory, if possible, on the same day.
• The connection in the valve must be made with a normal tightening, without straining the connection towards the valve, because this causes an expansion in the valve thread, resulting in a bad seal in subsequent samplings and an expense to replace it.

2. Sampling equipment the equipment used to sample the transformer oil is listed below: hose, cloth, glass hypodermic syringe, 3-way valve, and container.
3. Sampling method obtaining the sample is one of the most important steps in the analysis since the reliability of the test results depends on this. The main points are then cited to proceed with the taking of the oil sample.
   a. Locate the sampling valve in the transformer and clean the area of the valve where the sample will be taken in order to eliminate dust and excess matter accumulated on the outside.
   b. Remove the sampling valve plug and clean it with a clean blanket without using any solvents.
c. Use the appropriate conditions that allow us to clean the sample, as well as a free flow of oil through the connection without obstacles.

d. Attach the hose to the sampling valve.

4. Open the sampling valve and drain approximately 1 liter of oil in order to avoid taking a sample that is not representative.

Procedure for the Gas Chromatography Test 47 sediments In addition, that presents less movement of circulation with respect to the total volume of the tank.

5. Verify the following: the syringe must be with the plunger completely inwards, avoiding having spaces inside it. If the syringe is identified, verify that the serial number of the syringe corresponds to the sample to be taken.

6. Proceed to connect the hose-valve-syringe assembly.

7. Wash the syringe with the oil itself.

8. The bubbles present in the oil must be eliminated.

9. Take the oil sample.

10. Remove the accessories used.

   The identification of the sample has the main data of the analyzed transformer. The oil sample must be sent to the laboratory accompanied by the following information:

   a. Name of the Substation, Zone and Division.

   b. Transformer identification: - Operating voltage - Serial number - Oil brand (if known) - Equipment brand - MVA's capacity

   c. Purpose of the sampling.

   d. Date of sampling.

3. Results

Characteristic gas method

3.1. Case 1: Oil overheating

The gases generated for this type of failure are: Ethylene (C2H4), Acetylene (C2H2), Methane (CH4), together with Ethane (C2H6) and traces of the other gases [8].
3.2. Case 2: Paper overheating

When huge portions of carbon monoxide and dioxide (CO and CO2) are released, it is due to the overheating of the paper. This occurs when the event involves an oil structure and methane (CH4) and ethylene (C2H4) are also manifested. Considering that cellulose carbonizes at 150 °C, it is not surprising to find some degradation due to the standard operating temperature of the transformer. But, despite extensive diversification in the CO and CO2 production rate, the CO/CO2 ratio is regularly conserved in a narrow band between 0.1 and 0.3, where a high temperature tends to increase the CO/CO2 ratio, even with the appearance of an arc or partial discharges. High levels of gases that indicate the presence of an electrical fault with a high CO2/CO2 ratio are a clear indicator that cellulose is involved. This result can be accompanied by an analysis of furans; a high content of them will be indicative of a deterioration of the cellulose for thermal reasons.

3.3. Case 3: Internal archways

With enough acetylene (C2H2) and hydrogen (H2), with minimal amounts of ethylene (C2H4) and methane (CH4), As mentioned, if the cellulose is wrapped, carbon monoxide and dioxide (CO and CO2) will also be found. The small amounts of acetylene gas must be estimated with great measure since this gas originates almost exclusively by arc, and we know that this form of failure tends to develop a large failure.
3.4. Case 4: The Corona Effect

The corona effect is revealed when there are discharges that form around an energized conductor when the electric field exceeds a certain value. Low energy discharges typically cause hydrogen and methane, with low amounts of ethane and ethylene. In certain cases, significant amounts of hydrogen are created from the enormous amounts of water in critical places of the transformer, mainly in the presence of iron, which also forms oxygen. Cellulose with water in the presence of a corona effect can release more hydrogen than cellulose without water. This situation occurs especially when the sample is taken from the bottom, and there is also a high water value that can even be found in a free state [1].

3.5. Case I: H.E. No. 1

The first case to be treated is a power transformer immersed in oil. The year of manufacture is 1970. The electrical characteristics of said equipment correspond to a 15 MVA step-down transformer whose voltage level reduces from 60 kV to 10 kV. It is more than 40 years old. Manufacturing and initial diagnosis indicate: thermal decomposition, hot spots, electrical overheating, and small partial discharges, so the internal inspection of the equipment is very necessary.

The fault could be located before the transformer collapsed, and the fault was repaired and new chromatographic analyses were carried out.
3.6. Case II-H.E. No. 2
The second case to be treated is a power transformer immersed in oil. The year of manufacture is 1986. The electrical characteristics of said equipment correspond to a 17 MVA step-down transformer whose voltage level reduces from 60 kV to 10 kV. It has more than 30 years of manufacturing and the initial diagnosis indicates: thermal decomposition, hot spots, electrical overheating, and small partial discharges, so the internal inspection of the equipment is very necessary.

In this particular case, it can be observed that the fault is in the vacuum switch contacts, so the fault will be corrected and a new chromatographic analysis will be taken.

The chromatographic analysis tests performed on transformers 1 and 2 indicated the presence of gases above acceptable levels, which, according to the interpretation of the TDGC, Dornenburg Relations, and Roger's ratios, indicated the presence of faults such as thermal decomposition, hot spots, arc flash, and overheating for transformer 1, and the presence of faults such as thermal decomposition, hot spots, small partial discharges, and overheating for transformer 2.

When the transformers were disassembled, it was verified that the described faults were indeed present, although the 2 transformers were still in operation at the time of taking the oil sample. Had it continued in operation, the detected failures would have resulted in a collapse or untimely failure of the transformer, with its possible total destruction or even damage to other facilities, and, of course, the untimely cut of the electricity supply.

On the other hand, in transformer 3, the chromatographic analysis indicated that the gas levels were below acceptable values, so there were no internal faults, and the transformer was left in normal operation.
4. Discussion

The technique most commonly used today is the one that determines the total combustible gases (TCG) that are present in the gas above the oil. The main advantage of the TCG method compared to other methods that will be covered is that it is fast and applicable for use in the field. In fact, it can be used to continuously monitor a unit. However, there are a number of disadvantages to the TCG method. Despite this, it detects combustible fault gases (carbon monoxide, hydrogen, methane, ethylene, ethane, and acetylene) but not non-combustible gases (carbon dioxide, nitrogen, and oxygen). This method is applicable to those units that have a gas blanket and to completely oil-filled conservativetype units. Since most failures occur below the surface of the oil, gases must first saturate the oil and diffuse to the surface before accumulating on top. These processes take time, which delays the initiation of fault detection. The main disadvantage of the TCG method is that it only gives a single value for the percentage of combustible gases, but does not identify which gases are actually present. It is this last piece of information that is most useful in determining the type of failure that has occurred.

Another method for locating defective gases is the study of the gas layer, in which a sample of the gas is analyzed in the space above the oil to determine its composition. This method detects all the individual components. This method is currently not the best performed in the field. A properly equipped laboratory is preferred for the required separation, identification, and quantification.

Determination of these gases at the part per million level- The most informative method for detecting defective gases is the Dissolved Gas Analysis (DGA) technique. In this method, a sample of the oil is taken from the unit and the dissolved gases are extracted. The extracted gases are then separated, identified, and quantitatively determined. At present, this complete technique is best performed in the laboratory, as it requires precision operations.

Since this method uses an oil sample, it is applicable to all types of units and, like the general method, gas detects all individual components. The main advantage of the DGA technique is that it detects gases in the oil phase, allowing the earliest possible detection of an incipient fault. This advantage alone outweighs any disadvantages of this technique.

The motivation to focus on the diagnosis of estimating the DC isolation from the DGA is based on the fact that the isolation is the basic parameter of internal and external information of the equipment. [9]. IEEE Std C57.104-1991 is a standard. It points out that its use is for mineral oils in transformers, primarily appropriate for studying the oil in the tanks, which is not the case for the oil in the terminal box (phases).

The quality of the results is due to good practices. For sampling purposes, failure to follow the suggestions cited by the respective standards may indicate inadequate results and inappropriate decisions about maintenance work. [10]).

5. Conclusions

1.-Gas chromatography analyzes the oil that is made up of several hydrocarbon bases between 16 and 22 carbon atoms, and cellulose is a polymeric hydrocarbon. These elements constitute the insulation of a transformer. These elements decompose and give off gases when a thermal or electrical failure occurs.

2.-Gas chromatography predicts failures and thus improves the level of reliability in the operation of power transformers since it analyzes the gases released by oil and cellulose.

3.-Knowing the type of gases generated and their combinations, such as polymeric hydrocarbons, which indicate certain types of failures, corrective measures can be carried out before the unit collapses.

4.-Gas chromatography interprets the results, correlating them with incipient failures. The type and quantity of gases will determine when the unit is taken out of service or if there is time to schedule a stop of the equipment for inspection.

5.-It was demonstrated that the hypotheses raised are valid since it was confirmed that gas chromatography is a tool that helps in the primary detection of failures in transformers, identifies the type of failure, and makes timely decisions so that the equipment with failure internal service
is removed from service and repaired before major failures and service interruptions occur. Likewise, if the gas indicators are within the normal range, the transformers can continue in service reliably.

6.-Indeed, the chromatographic tests carried out on the transformers determine that the hypotheses raised are true and it is verified that gas chromatography helps predict early failures in the equipment.

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