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Insulation system diagnosis in power transformers using DGA analysis and Megger DC tests

Diagnóstico de sistemas de aislamiento en transformadores de potencia utilizando análisis DGA y pruebas Megger DC

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ABSTRACT

Dissolved gas chromatography (DGA) analysis and Megger DC insulation tests are performed to diagnose the condition of a power transformer. In this context, the objective of this study is to assess whether there is a relationship between both types of tests. To this effect, a database with DGA and Megger DC test protocols is analyzed, using the theory of variable correlation as well as current DGA techniques. The results allow stating that there is indeed a relationship between both tests under specific conditions. Therefore, the DC isolation status of a transformer can be estimated via DGA tests.

Keywords: insulation, correlation, chromatography, maintenance

RESUMEN

Los analisis por cromatografıa de gases disueltos (DGA) y las pruebas de aislamiento Megger DC son realizados para diagnosticar el estado de un transformador de potencia. En este contexto, el objetivo de este estudio es evaluar si existe una relacion entre ambos tipos de pruebas. Para ello, se analiza una base de datos con protocolos de pruebas DGA y Megger DC, utilizando la teorıa de correlacion de variables y las tecnicas actuales de DGA. Los resultados permiten afirmar que sı existe una relacion entre ambas pruebas bajo condiciones especıficas. Por lo tanto, se puede estimar el estado de aislamiento DC de un transformador a partir de pruebas DGA.

Palabras clave: aislamiento, correlacion, cromatografıa, mantenimiento

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Introduction

Power systems, as well as industrial sectors, are made up of a variety of electrical equipment that enables the flow of energy at adequate voltage levels for various applications. There is an indispensable piece of equipment responsible for supplying said voltage levels: the power transformer. Ensuring the continuous operation of this equipment is essential for the reliability of any electrical system, so timely maintenance allows foreseeing any failures with a negative impact in both technical and economic aspects.

The insulation of a transformer is exposed to the climatic conditions of its work environment, as well as to its operating characteristics. In general, insulation is a key component that deteriorates throughout the useful life of the equipment. This is where insulation evaluations like the Megger test take on importance, but they require a de-energized transformer to be executed. In the Megger DC test, a DC voltage is applied for 10 minutes to determine the static resistance of the insulation. On the other hand, dissolved gas chromatography (DGA) tests have become important in establishing the dielectric condition of the oil and detecting failures in a transformer from the combustible gases present in it, with the main advantage that they can be performed with energized equipment.

Problem statement

A power transformer's likelihood of failure depends on the behavior of its subsystems, which include the insulation system (IEEE Standards Association, 2017). The insulation of a transformer can be diagnosed through a set of electric tests, among them the Megger DC resistance test (Torkaman and Karimi, 2015), the dissipation factor tan-δ test (Malpure and Baburao, 2008), the power factor tip-up test (IEEE Standards Association, 2000), the dielectric frequency response test (IEC, 2006), and frequency response analysis (Sardar *et al.*, 2017). These tests require the transformer to be off-line, which leads to economic impacts for the owner.

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On the other hand, a DGA test can be performed with an online transformer and allows detecting the presence of different gases associated with its condition (IEEE Standards Association, 2019; IEC, 2015). Thus, this test might allow identifying the condition of a transformer's insulation based on statistical inference from a set of samples taken from a group of power transformers. This can help reduce the need to frequently disconnect transformers in order to perform insulation tests, as well as its economic impact.

Contributions

The main contribution of this paper lies in the existence of a correlation between two states of the DGA test and the Megger DC resistance test (regular and bad states). This finding was obtained from a statistical treatment applied to a set of real data on these two types of tests from 337 industrial power transformers. This encourages the application of the DGA test to predict potential insulation damages and reduce the need for off-line tests and their economic impact.

State of the art

In the area of dielectric oils chromatography, the interpretation of the gases present in a sample allows diagnosing faults in power transformers, such as the degradation of their insulation system (Díaz and Schmidt, 2014; Dhini *et al.*, 2020). The analysis consists of taking a dielectric oil sample and testing it in an accredited laboratory with a calibrated chromatograph, in order to obtain quantitative results regarding its gas composition, which are expressed in parts per million (ppm) and as a percentage (%).

Currently, the focus of DGA analysis consists of characterizing the behavior of combustible gases in the transformer with the aim of estimating the possible trends throughout its lifespan (Dukarm, 2019), in addition to estimating any internal failures of the equipment which may be derived from the aging of its insulation system (oil and paper) due to both thermal and electrical factors (Mahmoudi *et al.*, 2019). Carrying out DGA analysis on a regular basis allows observing the evolution of gases in the transformer, but there is no clear relationship between electrical failures and gas trends. Failures are usually determined via preventive electrical tests that directly evaluate transformer components (Fofana and Hadjadj, 2016) but require the disconnection of the equipment. However, there are four main DGA analysis techniques that are complementary and have the potential to detect failures in equipment components without affecting operation continuity (Juris *et al.*, 2020).

Recent works have combined current DGA analysis techniques with more complex modeling and probabilistic tools to improve status monitoring in power transformers. Some works use tools such as fuzzy logic and artificial neural networks (Prasojo *et al.*, 2020; Aciu *et al.*, 2021; Patekar and Chaudhry, 2019; Saravanan *et al.*, 2020), which allow for fault prediction and a better interpretation of the states of the transformer based on gas levels. On the other hand, the work by Aizpurua *et al.* (2019) focuses on the combination of probabilistic methods and soft computing to improve health monitoring in transformers under conditions of uncertainty.

Document structure

This article is organized as follows: the *Introduction* section presents the problem, a review of the state of the art and the contributions of our developed work; the section titled *DGA techniques* describes the theory associated with current DGA techniques for dielectric oil in transformers; the *Methodology* section presents the two models applied, the first of which is of the statistical type and focuses on the behavior of trends in fuel gases in addition to applying the theory of correlation of variables, while the second is a technical model to characterize the state of dielectric oil in transformers by applying the current techniques of DGA tests; in the *Results* section, the results obtained with the proposed models in their corresponding case studies are presents; and the *Conclusions* section draws the main conclusions of this study.

DGA techniques

The measurement of dissolved gases must be accompanied by appropriate interpretation, as provided by the DGA techniques, which aim to determine the relationship between the concentration of combustible gases and the presence of thermal or electrical faults in a power transformer. This section describes the current DGA techniques that are also recommended as fault identification methods in IEEE Std. C57.104-2019 (IEEE Standards Association, 2019).

Doernenburg analysis

Doernenburg analysis, or the Doernenburg ratios method, is employed to determine whether the origin of a transformer failure is thermal or electrical in nature, upon the basis of a group of relationships between the concentrations of different gases present in the transformer oil. This technique considers the concentration of Methane (CH_4), Hydrogen (H_2), Acetylene (C_2H_2), Ethane (C_2H_6), and Ethylene (C_2H_4). The Doernenburg ratios are calculated as follows:

$$R_1 = \frac{CH_4}{H_2} \tag{1}$$

$$R_2 = \frac{C_2H_2}{C_2H_4} \tag{2}$$

$$R_3 = \frac{C_2H_2}{CH_4} \tag{3}$$

$$R_4 = \frac{C_2H_6}{C_2H_2} \tag{4}$$

According to this interpretation method, the failures can be as follows: (a) thermal failures, which can occur when the transformer load exceeds the rated capacity over long periods of time, accelerating the natural rate of oil decomposition, generally at temperatures between 125 and 600 ^oC; (b) Corona effect failures, which is a low-energy partial discharge that occurs when dielectric oil is ionized, likely evolving into discharges in the cellulose of the insulating paper; and (c) internal arc failures, which is a short-duration, high-intensity discharge that can compromise the solid insulation of the transformer, where the oil has started its deterioration process (Piegar *et al.*, 2015). Table 1 shows the conditions of the Doernenburg ratios for each type of fault.

Table 1. Doernenburg fault diagnosis

Possible fault	R1	R2	R3	R4
Thermal decomposition (a)	>0,1	<0,75	<0,3	>0,4
Corona effect (b)	<0,1	–	<0,3	>0,4
Internal arcing (c)	0,1 to 1,0	>0,75	>0,3	<0,4

Source: (IEEE Standards Association, 2019)

Key gas analysis

This technique analyzes the individual concentration of gases. According to the temperature variations to which the oil is subjected, it is possible to find higher concentrations of certain gases. For instance, when there is an electrical failure, the temperature rises inside the transformer tank, and high concentrations of combustible gases are liberated. The key gas technique yields an estimate of gas generation for different temperature ranges in the transformer tank (IEEE Standards Association, 2008; Wannapring *et al.*, 2016).

According to Rogers (1978) and IEEE Standards Association (2008), the key gases analyzed with this method and their possible fault diagnoses are as follows:

Ethylene. When the concentration of this gas exceeds 63%, failure due to overheating in the oil is suspected, as it has lost its cooling and insulating properties (*i.e.*, thermal mineral oil failure). Typically, this type of failure is associated with a predominant concentration of ethylene and smaller proportions of ethane, methane, and hydrogen.

Carbon monoxide. If the concentration of this gas exceeds 92%, overheating is suspected in the cellulose due to fluctuations in the transformer's operating temperature, which is derived from load changes (*i.e.*, thermal mineral oil and cellulose fault).

Hydrogen. If the hydrogen concentration exceeds 86%, failure by corona effect is suspected. Low-energy partial discharges predominantly generate hydrogen, with small amounts of methane and traces of ethylene and ethane.

Hydrogen and acetylene. If the predominant gases are hydrogen and acetylene, exceeding concentrations of 60 and 30%, respectively, the fault is most likely of the electric arc type. In this case, the oil undergoes a breakdown in its structure and tends to evaporate in small quantities.

Rogers analysis

Rogers analysis, or the Rogers ratios method, evaluates gas concentration ratios to diagnose faults while considering the transformer tank's operation temperature. This technique evaluates ratios from Equations (1) and (2). Moreover, it incorporates the ratio between the concentrations of ethylene and acetylene (5) (Syafruddin and Nugroho, 2020).

$$R_5 = \frac{C_2H_4}{C_2H_6} \tag{5}$$

This fault identification technique that the temperature failures in the transformer tank are independent of electrical failures such as partial discharges (Wang, 2003). Thus, it allows identifying five types of failure, namely low-temperature thermal failure, which can be caused by the inrush current or high charging periods; thermal failure below 700 °C, typical of equipment with long periods of operation; thermal failure over 700 °C, which can be caused by the loss of the oil's cooling capacity; low-energy density arcing; partial discharges (Corona effect); and high-energy arcing, which can be caused by high energy discharges.

Table 2 presents the Rogers ratios for each type of fault. The limitation of this technique is that there can be many cases where the ratios do not meet the conditions established by the method, so the failure cannot be identified.

Table 2. Rogers fault diagnosis

Possible fault	R1	R2	R5
No failure	<0,1	0,1 to 1	>1
Low-temperature thermal	<0,1	0,1 to 1	1 to 3
Thermal fault $< 700^oC$	<0,1	>1	1 to 3
Thermal fault $> 700^oC$	<0,1	>1	<1
Corona effect	<0,1	<0,1	<1
Electrical arcing	0,1 to 3	0,1 to 1	>3

Source: (Sarria-Arias *et al.*, 2014)

Duval analysis

The Duval triangle analysis may be the most complete fault interpretation technique, as it allows identifying the six basic types of faults established in IEEE Standards Association (2019), plus mixtures of electrical and thermal faults. The Duval equations shown in (6)-(8) determine the percentages of methane (X), ethylene (Y), and acetylene (Z) over the sum of the three concentrations. These gases correspond to the increasing energy content or temperature faults: methane for low energy/temperature faults, ethylene for high energy/temperature faults, and acetylene for very high/temperature/arcing faults.

$$\%C_2H_2 = \frac{X}{X+Y+Z} \times 100 \tag{6}$$

$$\%CH_4 = \frac{Y}{X+Y+Z} \times 100 \tag{7}$$

$$\%C_2H_4 = \frac{Z}{X+Y+Z} \times 100 \tag{8}$$

Graphically, the concentrations of the gases shown above correspond to the coordinate axes of an equilateral triangle, and the intersection of lines parallel to the axes allows finding the zone of possible failure in a transformer. Figure 1 shows the Duval triangle and its different fault zones, and Table 3 presents their corresponding diagnoses.

The mixed fault zone (DT) allows classifying both thermal and electrical failures. This is a factor related to equipment that operates for long periods of time, as characteristic gases will necessarily be generated for both types of failure.

DGA tests

Dissolved gas chromatography testing in a power transformer consists of systematically calculating the concentrations of the combustible gases present in a sample of dielectric oil. Its results are quantitative and are expressed in parts per million (ppm) and as a percentage (%).

The results obtained for each of the combustible gases are compared with the ranges stipulated by Table 1 of the IEEE

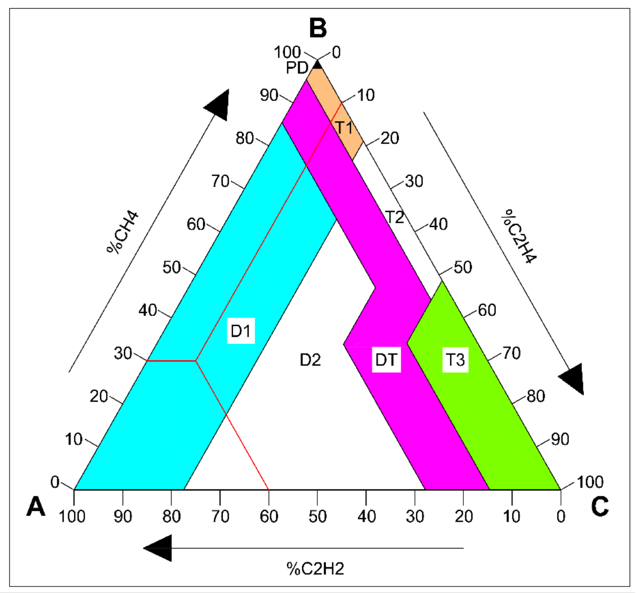

Figure 1. Duval triangle for fault diagnosis
Source: (Sarria-Arias *et al.*, 2014)

Table 3. Duval fault diagnosis

Zone	Possible fault	Gas limit values
PD	Partial discharge	$CH_4 = 98$
D1	High-energy discharge	$C_2H_4 = 36$; $C_2H_2 = 13$
D2	Low-energy discharge	$C_2H_4 = 23; 40$ $C_2H_2 = 13; 29$
T1	Thermal fault $< 300^oC$	$CH_4 = 98$; $C_2H_4 = 20$ $C_2H_2 = 4$
T2	Thermal fault 300^oC to 700^oC	$C_2H_4 = 20$; 50; $C_2H_2 = 4$
T3	Thermal failure $> 700^oC$	$C_2H_4 = 50$; $C_2H_2 = 15$
DT	Mix of thermal/electrical faults	$C_2H_4 = 13$; 4; 29; $C_2H_2 = 40$; 50

Source: (Sarria-Arias *et al.*, 2014)

Std. C57.104-2008 (*Dissolved gas concentrations*) (IEEE Standards Association, 2019). These ranges in ppm have been classified and are presented in Table 4.

Table 4. Transformer conditions and ppm gas ranges for the separate gases method

Gas	1 (Normal)	2 (Regular)	3 (Bad)	4 (Dangerous)
H_2	100	101 – 700	701–1 800	>1 800
CH_4	120	121 – 400	401–1 000	>1 000
CO	350	351 – 570	571–1 400	>1 400
C_2H_4	50	51 – 100	101 – 200	>200
C_2H_6	65	66 – 100	101 – 150	>150
C_2H_2	1	2 – 9	10 – 35	> 35

Source: (IEEE Standards Association, 2019)

According to Table 4 and the criteria established by the IEEE, condition 1 represents a transformer in a normal operating state, condition 2 denotes an equipment that must be analyzed using at least one of the DGA techniques, condition 3 implies failures in the oil (all the DGA techniques must be applied), and condition 4 represents a high probability that the oil is undergoing decomposition, so the transformer must be intervened by the manufacturer and be temporarily or permanently withdrawn from operation.

Megger DC resistance test

In these tests, DC voltage is applied under different configurations to the primary and secondary windings of the transformer. This, in order to observe the behavior of the insulation for 10 min. Good insulation should increase as time increases. The settings for the test are primary winding *vs.* ground, primary winding *vs.* secondary winding + ground, and secondary winding *vs.* ground.

The most important parameter in this test is the polarization index (*PI*), which is calculated using Equation (9). The PI is a dimensionless qualifying factor of the condition of the insulation system for the conditions of temperature and humidity under which a transformer operates.

$$PI = \frac{R_{insulation-10minutes}}{R_{insulation-1minute}} \tag{9}$$

Section 7.2.13.4 of IEEE Std. C57.152-2013 (*Polarization index test*) (IEEE Standards Association, 2013) qualifies PI conditions according to Table 5.

Table 5. Evaluation of the polarization index

IP	Condition	Criteria
≥ 2	1 (Excellent)	New transformer
$1,25 \leq IP < 2$	2 (Good)	Normal operation
$1,1 \leq IP < 1,25$	3 (Regular)	Under surveillance
$1 < IP < 1,1$	4 (Bad)	Corrective maintenance
< 1	5 (Dangerous)	Factory repair or decommissioning

Source: (IEEE Standards Association, 2013)

Methodology

The methodology consisted of applying two analyses. The first one was a comparative statistical analysis using the correlation between two conditions of the DGA test and the Megger DC resistance test, and the second one compared the DGA techniques in order to identify advantages and disadvantages for the detection of thermal and electrical faults. These analyses were applied to 337 mineral oil-filled industrial power transformers, whose main characteristics are shown in Table 6.

Table 6. Characteristics of the studied transformers

Power range [kVA]	Primary voltage range [kV]	Secondary voltage range [kV]	Manufacturing year range
75 - 22 000	0,480 - 115	0,215 - 110	1996 - 2016

Source: Authors

Figure 2 describes the methodology from the acquisition of the database to the results. Initially, the information in the database was organized according to the type of test (DGA or Megger DC resistance) and its results. Once the data were classified, they were separated for use in the proposed study cases.

At this stage, it was verified whether each transformer had a DGA test and a Megger DC test. The tests were classified according to the conditions established in the IEEE standards C57.104-2008 (IEEE Standards Association, 2019) and C57.152-2013 (IEEE Standards Association, 2013). The transformers with DGA tests in condition 4 and Megger DC tests in condition 5 were discarded, as these conditions imply a high risk of failure and are dangerous for the operation.

For the correlation analysis, two cases were studied. The first case (Case I) aimed at determining the correlation between conditions 2 (regular) and 3 (bad) in the DGA analysis and conditions 3 (regular) and 4 (bad) in the Megger DC tests. This, in order to determine the relationships between the states that can lead to future failures in the transformers, *i.e.*, the probability that a transformer with regular or bad conditions in the DGA analysis has the same conditions in the Megger DC tests.

The second case (Case II) sought to find the correlation between the tests exhibiting condition 1 (normal) in the DGA analysis and conditions 3 and 4 in the Megger DC test, aiming to evaluate the probability that one transformer with a normal DGA condition could be in a regular or bad state according to the Megger DC test.

To determine the correlation, Pearson's coefficient (r) was employed, which is a quantifying value of the linear relationship between two variables. This coefficient can take values from -1 to 1, with the following characteristics: a value of -1 indicates an inverse (negative) proportional relationship, a value of 1 indicates a direct (positive) proportional relationship, and a value of 0 indicates that there is no relationship between the variables.

The Pearson coefficients obtained for Case I were subjected to a hypothesis test in order to verify their significance. The theory of hypothesis testing for small samples was used to determine whether the coefficient was significantly different from 0. This, by means of the t-student distribution (Walpole *et al.*, 2017; Devore, 2016). This test confirms whether the DGA states and the Megger DC conditions are actually related or only show a relationship because of chance (Devore, 2016). The selected confidence level was 95%.

Finally, considering the 337 power transformers, a technical comparison between the DGA techniques was performed. This analysis encompassed the application of the aforementioned DGA techniques to each transformer in order to explore different types of failures as well as matches between techniques. Furthermore, the results were contrasted with the correlations obtained in previous study cases.

Results

According to the classifications in the standards for the DGA and Megger tests, the results in the DGA tests place 86,65% of the transformers in normal conditions, 9,50% in regular conditions, 3,56% in a bad condition, and only 0,30% in dangerous conditions. These data can be seen in Figure 3, which shows the distributions of the DGA tests.

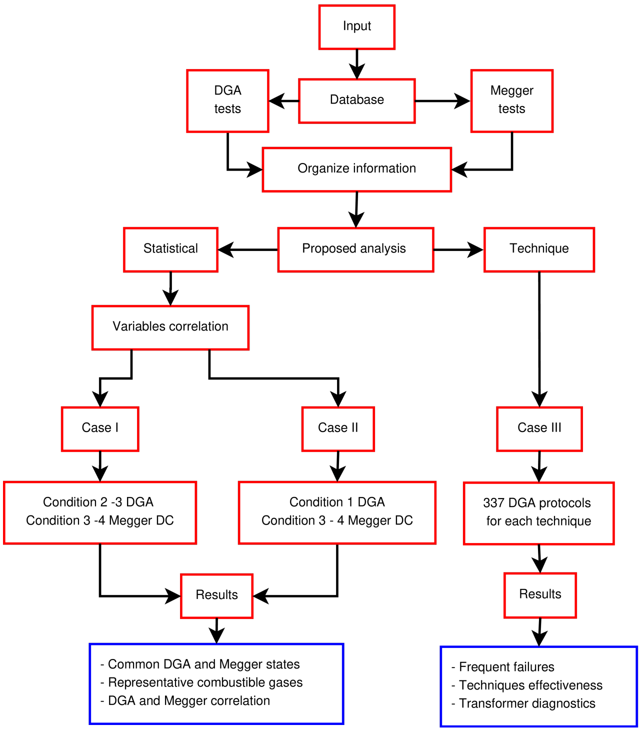

Figure 2. Methodology flow chart
Source: Authors

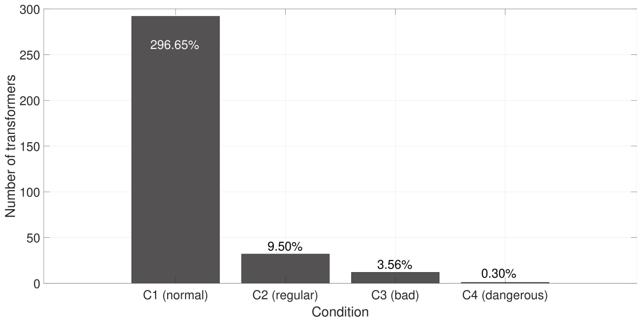

Figure 3. DGA tests classification
Source: Authors

As for the Megger DC resistance tests, 10,68% of the transformers were found to be in excellent conditions, 63,80% in normal conditions, 10,39% in regular conditions, 2,97% in bad conditions, and 0% in dangerous conditions. 12,17% of the transformers fall into the category dubbed *No protocol*, which refers to the transformers that did not undergo a Megger DC resistance test, since it was not possible to de-energize them. These transformers were excluded from all study cases. Figure 4 shows the Megger DC resistance test results according to the conditions detected.

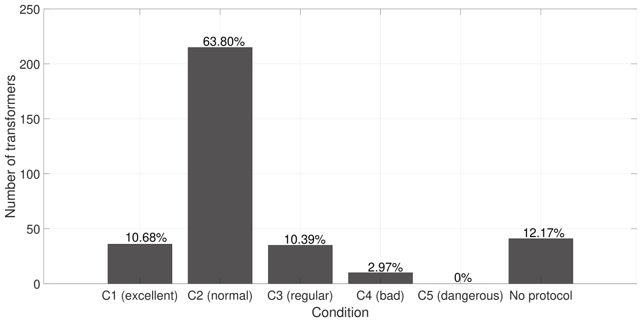

Figure 4. Megger DC test classification
Source: Authors

Analysis of Case I

For this case, out of the 337 transformers, a total of 44 DGA tests reported conditions 2 (regular) or 3 (bad), while, regarding the Megger DC tests, there was a total of 45 transformers with conditions 3 (regular) or 4 (bad). Out of these, there were only 38 transformers that had one of the DGA conditions and one of the Megger DC test states in common. Table 7 shows the conditions of these 38 power transformers.

To calculate the correlation coefficient, Equations (10) and (11) were used, where X represents the transformer's DGA test condition, Y is its Megger DC test state, and $\overline{X}$ and $\overline{Y}$ denote the averages of each condition, which were $2,2894$ and $3,2632$ respectively. Table 8 presents the results of each term in Equation (10).

$$covariance = \frac{\sum((X-\overline{X})\times(Y-\overline{Y}))}{n-1} \tag{10}$$

$$r = \frac{covariance}{S_x \times S_Y} \tag{11}$$

Table 7. DGA and Megger DC condition values for Case I

Transformer ID	DGA (X)	Megger DC (Y)	Transformer ID	DGA (X)	Megger DC (Y)
007	3	4	217	2	3
023	2	3	218	2	3
031	2	3	219	3	4
035	2	3	220	3	4
049	2	3	224	3	4
069	2	3	237	3	4
070	2	3	238	2	3
101	2	3	239	2	3
110	2	3	242	2	3
115	2	3	243	2	3
137	2	3	244	3	3
152	3	4	245	3	3
156	3	4	270	2	3
186	2	3	276	2	3
190	2	4	287	2	3
203	3	4	297	2	3
204	3	4	304	2	3
211	2	3	332	2	3
212	2	3	333	2	3

Source: Authors

The results obtained show a covariance of $0,1650$ and a correlation coefficient of $0,8045$. The latter indicates that, if a transformer is in condition 2 (regular) or 3 (bad) in the DGA tests, then it can be said that its insulation is at least in condition 3 (regular) or in condition 4 (bad) of the Megger DC test, with a correlation of 80,45%.

The correlation coefficient obtained was subjected to the hypothesis test described in Table 9, with H_0 being the null hypothesis and H_1 the alternative hypothesis. A t-test based on Student's t-distribution with $N-2$ degrees of freedom and a standard deviation calculated with Equation (12) was applied to evaluate the hypotheses by means of the t_0 statistic (Equation (13)).

$$S_r = \sqrt{\frac{1-r^2}{N-2}} \tag{12}$$

Table 8. Transformer correlation coefficient for Case I

Transformer ID	X-$\overline{X}$	Y-$\overline{Y}$	(X-$\overline{X}$) × (Y -$\overline{Y}$)
007	0,7105	0,7368	0,5235
023	-0,2895	-0,2632	0,0762
031	-0,2895	-0,2632	0,0762
035	-0,2895	-0,2632	0,0762
049	-0,2895	-0,2632	0,0762
069	-0,2895	-0,2632	0,0762
070	-0,2895	-0,2632	0,0762
101	-0,2895	-0,2632	0,0762
110	-0,2895	-0,2632	0,0762
115	-0,2895	-0,2632	0,0762
137	-0,2895	-0,2632	0,0762
152	0,7105	0,7368	0,5235
156	60,7105	0,7368	0,5235
186	-0,2895	-0,2632	0,0762
190	-0,2895	-0,2632	0,0762
203	0,7105	0,7368	0,5235
204	0,7105	0,7368	0,5235
211	-0,2895	-0,2632	0,0762
212	-0,2895	-0,2632	0,0762
217	-0,2895	-0,2632	0,0762
218	-0,2895	-0,2632	0,0762
219	0,7105	0,7368	0,5235
220	0,7105	0,7368	0,5235
224	0,7105	0,7368	0,5235
237	0,7105	0,7368	0,5235
238	-0,2895	-0,2632	0,0762
239	-0,2895	-0,2632	0,0762
242	-0,2895	-0,2632	0,0762
243	-0,2895	-0,2632	0,0762
244	0,7105	0,7368	0,5235
245	0,7105	0,7368	0,5235
270	-0,2895	-0,2632	0,0762
276	-0,2895	-0,2632	0,0762
287	-0,2895	-0,2632	0,0762
297	-0,2895	-0,2632	0,0762
304	-0,2895	-0,2632	0,0762
332	-0,2895	-0,2632	0,0762
333	-0,2895	-0,2632	0,0762

Source: Authors

Table 9. Hypotheses raised to asses the significance of the correlation coefficient

Hypotheses raised	
$H_0 : r = 0$ indicates that the coefficient obtained comes from a population whose correlation is 0	$H_1 : r \neq 0$ indicates that the coefficient obtained comes from a population whose correlation is different from 0

Source: Authors

$$t_0 = \frac{r}{\sqrt{\frac{1-r^2}{N-2}}} \tag{13}$$

The t-test states that, if $t_0 > t_{(\alpha/2,N-2)}$, the null hypothesis is rejected, which means that the correlation coefficient of the population is different from 0, *i.e.*, there is a relationship between the variables. On the other hand, if $t_0 \leq t_{(\alpha/2,N-2)}$, the null hypothesis is accepted, meaning that the correlation of the population is equal to 0.

In the current study case, $t_0 = 8,1269$, and the selected significance level was $\alpha = 0,05$, which gives $t_{(\alpha/2,N-2)} = 2,0281$. These results lead to the rejection of the null hypothesis, which means that the sample comes from a population where the correlation is not equal to 0, with a confidence level of 95%.

Analysis of Case II

In this case, the number of transformers with a DGA test condition 1 (normal) was 292, and the transformers with the Megger DC resistance test conditions 3 and 4 were the same 45 of Case I. When comparing the conditions for these transformers, it was found that only seven of them share the conditions described above.

In these transformers, the PI meets two out of the three configurations of the Megger DC test, and the one that did not comply with the standard exhibits a value close to that required. In these protocols, the behavior of Case I was not observed; three or two configurations of the Megger DC test were not met, and their results were far from the required limit.

By applying correlation theory to the data in Table 10, it is observed that $\overline{X} = 1$ and $\overline{Y} = 1$. The covariance, as well as the standard deviations S_X and S_Y, have values equal to 0, so the correlation coefficient is an indeterminacy.

Table 10. DGA and Megger DC condition values for Case II

Transformer ID	DGA (X)	Megger DC (Y)
135	1	3
148	1	3
158	1	3
197	1	3
235	1	3
236	1	3
323	1	3

Source: Authors

Table 11. Total combustible gases (TDCG) conditions for Case II

Transformer ID	TDCG (ppm)	Limit allowed by the standard
135	193	< 720 ppm
148	367	
158	205	
197	65	
235	384	
236	377	
323	134	

Source: Authors

When a total combustible gases (TDCG) analysis was conducted in these seven transformers, it was found that the highest concentration was 384 ppm and the lowest one was 65 ppm (Table 11). Both values match the normal conditions of the IEEE Std. C57.104-2008 (IEEE Standards Association, 2019), with 0-720 ppm being the allowed range.

The irregular insulation results can be attributed to climatic conditions when the Megger DC tests were run, as a high humidity directly affects the measurement. For this case, it is not possible to apply variable correlation theory, since the DGA and Megger states are the same for all tests. A larger sample would be needed to identify new relationships between the states analyzed.

Analysis of Case III

When the aforementioned DGA techniques were applied to the transformers, it was found that most of them showed no identifiable faults. The majority of the faults found via the Doernenburg, key gas, and Rogers methods were thermal in nature, whereas the Duval technique reported a higher percentage of low-energy partial discharge electrical failures.

In the Doernenburg analysis, 92,88% of the transformers showed no faults. Only 21 transformers reported failures, which were classified according to the Doernenburg ratios (Table 1). 11 of these could not be identified, since at least one of the ratios was indeterminate, implying the need to rerun the tests. As for the rest, eight faults were identified as thermal and two as internal arc failures (Figure 5).

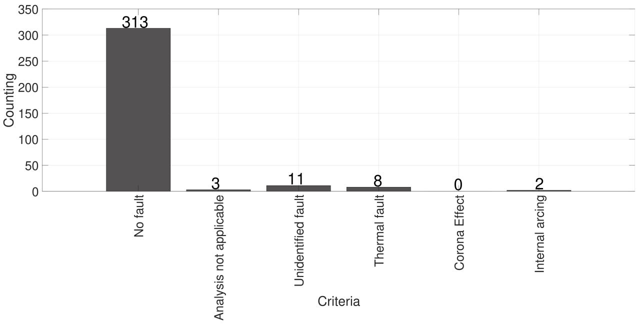

Figure 5. Results for the transformers analyzed via the Doernenburg technique
Source: Authors

When comparing the Doernenburg analysis results against those of the correlation analysis, it was noted that there were more transformers in regular and bad conditions than transformers with identifiable faults according to the Doernenburg analysis.

The key gas technique also classified the majority of the transformers as being in a normal state. The most representative failure with this method was cellulose overheating, with carbon monoxide being the representative gas (Figure 6).

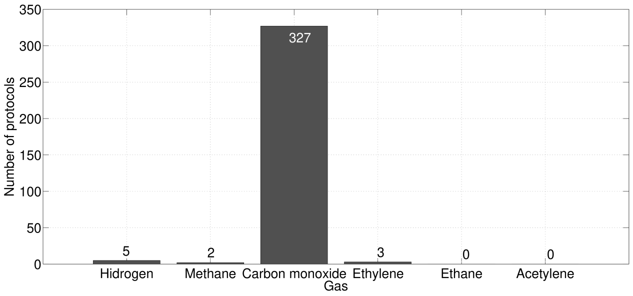

Figure 6. Results regarding relative gas distribution in the 337 power transformers
Source: Authors

As for the Rogers ratios method, 31,45% of the transformers were not suitable for analysis due to indeterminacies in the ratios, 20,47% did not have faults, 15,43% reported faults at low temperatures, and the rest exhibited thermal faults below 700 ^{o}C. No electrical faults were found with this method, which supports its ability to better predict thermal faults.

According to the Duval triangle, 81,31% of the results correspond to lower-intensity partial discharge electrical faults, which are typical of transformers with long periods of operation. Even though this is a minor fault type, it is likely that it will evolve into more critical faults in the triangle. This is the only method that identified more faulty transformers in comparison with the correlation analysis, given that Duval analysis evaluates failures in early stages, while correlation requires more advanced failure conditions.

Conclusions

The results obtained for the study cases with real data from 337 transformers allow concluding that there is a correlation between DGA and Megger DC tests. Therefore, the insulation status of a transformer can be diagnosed based on the results of gas concentration analysis, with a correlation of 80,45% when the DGA condition is regular or bad. Estimating the insulation status of equipment without the need to disconnect it constitutes an advantage, *i.e.*, it minimizes its downtime and increases its availability.

Based on the theory and the development of the exposed models, it was observed that DGA tests and the available analysis techniques are robust tools for diagnosing the state of the insulation system in a power transformer. The analyses carried out made it possible to distinguish between thermal and electrical faults according to the presence of specific combustible gases. The gases with the highest likelihood in a DGA test were hydrogen and carbon monoxide, which are inherent to the operation of a power transformer. In contrast, it was less likely to find acetylene in high concentrations, since it is linked to dangerous electrical fault conditions.

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CRediT author statement

All authors contributed equally to the research.

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