Automatic Analysis System for Monitoring and Diagnosing the Condition of Transformer Insulating Oils

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***Abstract*—Mineral insulating oil degrades over time due to oxidation, accelerated by metallic compounds, oxygen, water, and heat. This degradation leads to color changes, acidic compound formation, and, in advanced stages, sludge precipitation. Monitoring these changes requires periodic chemical, physical-chemical, and chromatographic analyses, which can be time-consuming and costly. This work presents a pilot unit that simulates transformer conditions and enables real-time, automated measurement of oil color, dissolved oxygen, conductivity, and pH, allowing for reliable degradation diagnostics. The results indicated an upward trend in analyzed parameters, showing that degradation begins quickly. The obtained values provided a more precise diagnosis of oil condition. The statistical correlations further justify the findings, demonstrating the effectiveness of automated monitoring. Implementing this automation can significantly reduce equipment downtime and unnecessary laboratory analyses, with chemical tests serving as confirmation.**

***Index Terms*—analytical automation, electrical equipment reliability, oil degradation, sensors, transformer maintenance.**

I. INTRODUCTION

Insulating oils are called mineral oils, to distinguish them from vegetable and animal oils. Insulating oils are produced from crude oil, which is geologically classified as rock. Crude oil consists of a mixture of several classes of hydrocarbons with water, sand, and most often sulfur [1].

The use of mineral insulating oil in transformers dates back to the end of the 19th century and, despite all the technological advances, it continues to be the most widely used insulation system. Periodic analyses of the quality of insulating oil are extremely important to ensure the reliable operation of power transformers, which is directly linked to the insulating oil preservation system [2].

It is estimated that 95% of the equipment present in the plants of electricity distribution companies in Brazil uses mineral-insulating oil. The composition of the mineral-insulating oil and its characteristics depend on the nature of the petroleum from which it was extracted and the process used in its preparation [3-4].

The power transformer is an important and expensive piece of equipment in the context of electrical power systems. The appropriate application of closed-insulating oil preservation systems contributes to the economical operation of this equipment (increased loading, reduced maintenance, and aging) and the extension of the corresponding service life [1], [5].

Switches used in substations operate with insulating oils and due to the aging of the oil or poor maintenance, it allows the penetration of contaminants, such as aldehydes, ketones, and carboxylic acids, accelerating the aging process [6].

The function of insulating oils in transformer switches is to increase dielectric strength and heat dissipation. Mineral insulating oil in power transformer switches is subject to deterioration due to mechanical and chemical conditions of use. In its dielectric function, the oil acts to insulate bare metal surfaces, fill empty spaces between energized parts, and impregnate the solid insulation of the transformer. In its heat sink function, the oil serves as a vehicle for transferring heat generated due to losses in the energy conversion process [3].

The current assessment of the quality of the oil in operation is made through the interpretation of measurements made of certain indices/characteristics based on applied admissible limits. The frequency of checking the index measurements is often not done in time to avoid failures and/or replacement of the equipment [7].

Insulating oil testing is well-established for certain types of high-voltage equipment, especially power transformers. For this equipment, diagnostic tests are successfully applied to determine abnormal operating conditions due to faults. Conditions that lead to oil degradation due to abnormal energy dissipation are generally referred to as defects. Defects are not necessarily catastrophic conditions, however, defects can lead to the failure of electrical equipment. In the case of transformers, deficient conditions can be determined by measuring oil degradation products (usually gases) being produced as a result of abnormal energy dissipation in the unit [8].

Frequently, the quality of oil in operation is assessed by comparing measurements of certain physical and chemical characteristics with predetermined limit values. The time between two consecutive measurements can be so long that failures and/or replacement of the equipment cannot be avoided [9].

In addition to oxidation products, other contaminants such as water, solid particles, and polar compounds soluble in oil can accumulate during service and alter their properties [10-11]. The deterioration of other materials that may interfere with the proper functioning of electrical equipment and shorten its service life can also be indicated by changes in oil properties [12].

Currently, the safety frequency for maintenance on Load Tap Changers (LCTs) of Regulator Transformers is a number set by the manufacturer according to the LCT model and does not take into account the average current to which it is subjected. The implications of this method are unnecessary maintenance and interruptions at important points in the electrical system [13].

This work aimed to develop a system for automatic monitoring and diagnosis of the operating condition of the On-Load Tap Changer (OLTC) of Transformers in the Transmission Substations of an electricity generating company, integrating the evaluation of the performance of the insulating oil through the correlation of the dissolved oxygen (DO), pH and conductivity parameters with the aid of online sensors and the Flow Injection Analysis (FIA) used in the color measurement.

II. METHODOLOGY

A. *Pilot unit for assessing the degradation of insulating oil:*

The pilot unit (Figure 1A) built to evaluate the degradation of switch-insulating oil was implemented in the Laboratory and a vacuum pump was used to circulate the oil through the system. For color analysis, a Flow Injection Analysis (FIA) was used (Figure 1B) The samples were removed from the system line using capillary tubes coupled to an outlet via a peristaltic pump of the prototype FIA.

Approximately 40 liters of new AV 58 mineral insulating oil (Petrobras oil) were used to study the oil aging process. Oil samples were collected through the outlet tap (Figure 2A) and FIA cuvettes were used as acquisition cells with capillary tubes for color analysis (Figure 2B). After activating the peristaltic pump, the oil removed from the line was taken through the capillary tubes to the cuvette placed in the absorption chamber of the spectrophotometer.

Fig. 1. Pilot unit for simulating insulating oil degradation (A) and Flow Injection Analysis (FIA) coupled to a UV-VIS spectrophotometer (B).

B. *Analysis of color, pH, dissolved oxygen and conductivity parameters:*

The analytical procedure for color analysis adopted to prepare the analytical curve was as follows: after preparing the color standard solution using 0.0623 grams of potassium chloroplatinate, 0.05 grams of cobalt chloride and 10 mL of hydrochloric acid, the solution was calibrated with supra-pure water in a 50 mL flask. For the intermediate color standard, several portions of the standard solution were diluted with volumes of 0.5 mL; 1.0 mL; 1.5 mL; 2.0 mL, and 2.5 mL, in 50 mL flasks, the blank was made, and then the reading was started with the color standard solutions in triplicates, through the absorption spectrum it was determined that the maximum absorbance was at the wavelength of 420 nm.

The curve found ($y=0.9983x$) was linear in the analyzed range with a correlation of 0.9991, which proves that the method follows Beer's law within this range.

The results for the detection limit ($5.01x10^{-3}$ mg.L^{-1} of Pt-Co) and quantification limit (0.05 mg.L^{-1} of Pt-Co) showed that the technique was adequate even at low concentrations.

The study of accuracy and repeatability was carried out with color analysis in three types of oils, where the analytical quality of the methodology was verified.

To analyze the pH, dissolved oxygen (Figure 2C), and conductivity parameters (Figure 2D), online sensors (which do not require oil sampling) were used, which were coupled to the system.

The sensors were calibrated at the factory. After the pilot unit was installed, they were constantly calibrated by comparing the values obtained by the sensors with those obtained on benchtop equipment.

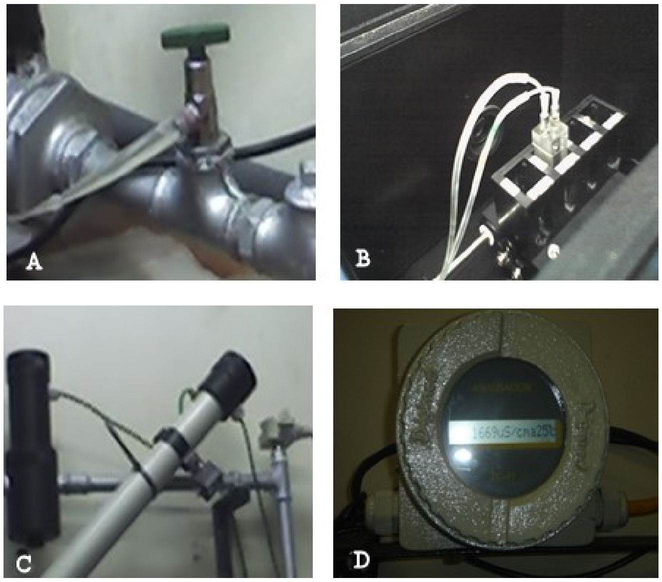

Fig. 2. Detail of the oil outlet tap (A), the absorption cell for FIA color analysis (B), dissolved oxygen sensor (C) and conductivity sensor (D).

III. RESULTS AND DISCUSSION

A. *Descriptive statistics and variability of results:*

Monitoring of the insulating oil was carried out for 54 days with the temperature set at 60 °C. The results of the descriptive statistics found for the measurements of the parameters color, DO, pH, and conductivity are shown in Table 1.

TABLE 1. DESCRIPTIVE STATISTICS FOR THE PHYSICAL-CHEMICAL PARAMETERS ANALYZED.

Descriptive statistics	Color ($mg.L^{-1}$ Pt-Co)	Dissolved oxygen ($mg.L^{-1}$)	pH	Conductivity ($mS.cm^{-1}$)
Mean	0.15	7.09	4.93	1.83
Median	0.16	7.58	4.94	1.83
Standard deviation	0.05	2.33	0.45	0.41
Minimum	0.01	2.35	4.23	1.24
Maximum	0.24	9.83	5.78	3.42

The Figure 3 shows the variability of the results with the anomalous data found. The greatest variability of the results was presented by DO and the smallest variability was in color, anomalous results (outliers) were found only for conductivity. Although the color had significant variations due to the problem of the appearance of suspended material in the oil, this variation was not observed in the box plot graph.

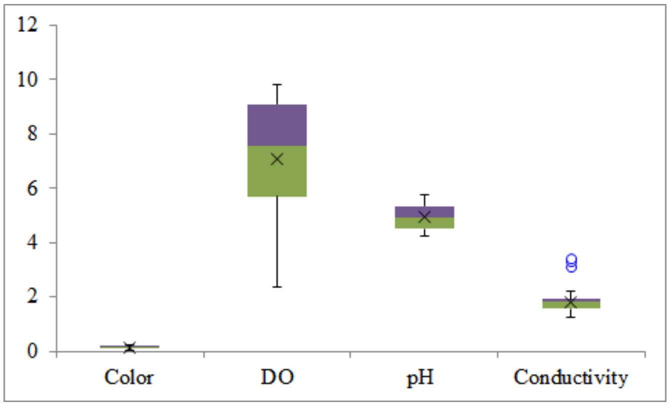

Fig. 3. Variability of results. DO: dissolved oxygen.

B. *Color results:*

Color is a physical property; new oil has a pale yellow color and is transparent. The color changes and darkens as the oil deteriorates, so it can be deduced that there is also a large oxidation process in the oil as a result of the increase in the content of aldehydes, ketones, and carboxylic acids [14-15].

Pure AV 58 oil in three stages (new, used, and degraded) (Figure 4), without dilution, was analyzed using the flow injection system to automate the analysis and a UV-Vis molecular absorption spectrophotometer. The Figure 4 shows also the absorption spectrum of the three samples; the absorbance was read at a wavelength of 420 nm.

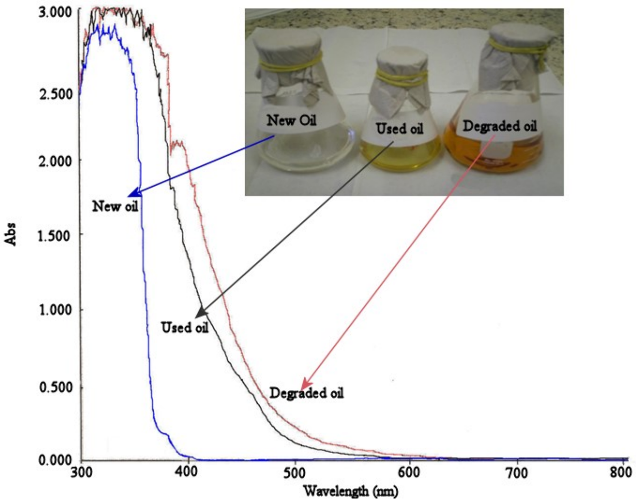

Fig. 4. Absorption spectrum of AV-58 oil in three stages.

The results observed in the exploratory research on the three types of oil showed that the color concentration increases with the oil aging process. According to the National Agency of Petroleum, Natural Gas and Biofuels (ANP) in its resolution No. 900/2022, which sets out the specifications for type A and type B insulating mineral oils, of national or imported origin [16], marketed in the national territory, the insulating mineral oil must be clear, clean and free of suspended material, when the visual method is used, about the color itself, of the minimum without detection and the maximum of 1.0 $mg.L^{-1}$ of Pt-Co.

The color and appearance of an oil are determined by transmitted light and are expressed by a numerical value based on the comparison of a series of color standards. It is not a critical property, but it can be useful for comparative evaluation. A rapidly increasing color number may be an indication of oil degradation or contamination [14], [17].

In addition to color, the appearance of the oil may show cloudiness or sediment. These may indicate the presence of free water, insoluble sludge, carbon, fibers, dirt, or other contaminants [18]. The presence of these materials in suspension causes fluctuations in absorbance measurements that can lead to erroneous results. A pre-stage of filtering the oil before entering the absorption chamber would avoid this problem.

In the study of oil monitoring in the pilot unit, the range found for color was 0.01 mg.L^{-1} of Pt-Co at the beginning of monitoring with a maximum of 0.24 mg.L^{-1} of Pt-Co and an average of 0.15 mg.L^{-1} of Pt-Co over the 54 days of oil evaluation. From the graph shown in Figure 5, it was possible to observe a regular (R^2=0.6536) trend of increasing color over time (y = 0.0027x + 0.0785).

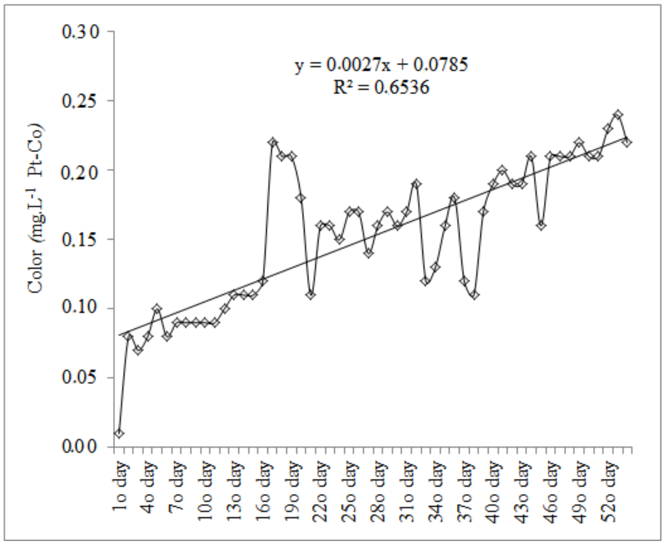

Fig. 5. Trend graph for color.

The new insulating oil is usually clear. Darkening during service indicates deterioration. As a result, color changes in the oil, formation of acidic compounds, and, in a more advanced stage of oxidation, sludge precipitation may occur. These changes in characteristics are usually accompanied by periodic physical-chemical analyses.

The color test is usually performed by a comparative test with color standards; it is not a critical test, but useful in assessing the oxidation state of the insulating oil. The replacement of color standards with a spectrophotometer and a Flow Injection Analysis (FIA) system allowed online color analysis and the provision of an assessment of oil degradation through this physical parameter [19-20].

A. *Dissolved Oxygen and pH results:*

The concentration range found for DO was 2.35 mg.L^{-1} at the beginning of monitoring to 9.83 mg.L^{-1} with an average of 7.09 mg.L^{-1} over the 54 days of oil evaluation. From the graph shown in Figure 6, it was possible to observe a strong and linear (R^2 = 0.7994) trend of increasing DO over time (y = 0.1322x + 3.4551).

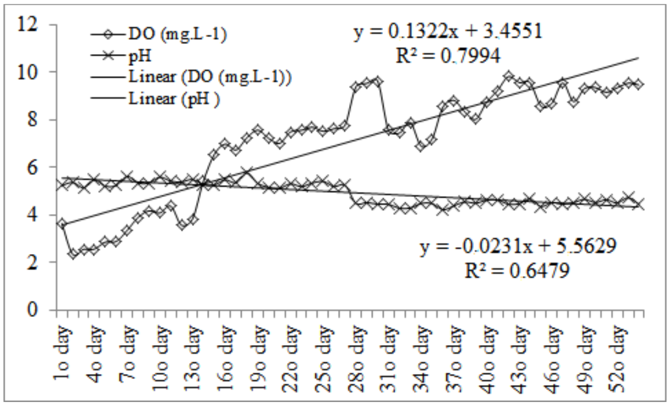

Fig. 6. Trend graph for DO and pH.

Water may exist in oil in dissolved, undissolved (suspended), or free (deposited) forms. The amount of water in solution in the oil depends on the temperature and the degree of refining. The higher the temperature, the greater the amount of water dissolved in the oil, and the better refined the oil, the lower the water solubility [21-23].

The accepted oxidation mechanism is one in which the process is initiated by the formation of hydroperoxides resulting from the fixation of oxygen by a free radical. This radical would be formed by the loss of a hydrogen atom from the hydrocarbon, through the catalytic action of the metals present in the system, mainly copper [24-25].

There is a correlation between the amount of water in the insulating mineral oil and the dissolved oxygen content since a high dissolved oxygen content means the presence of water in the insulating mineral oil [26-27].

Oxygen in the insulating oil causes a process called oxidation, which is a set of complex and slow chemical reactions in which hydrocarbons react with oxygen. This degradation is considered a homogeneous oil oxidation by dissolved molecular oxygen. The spontaneity of propagation is the main characteristic, even more important than initiation. Oil oxidation is a complex succession of radical reactions known as "auto-oxidation" [28-29]. The range found for pH was 5.78 at the beginning of monitoring to 4.23 with an average of 4.93 over the 54 days of oil evaluation. From the graph shown in Figure 6, it was possible to observe a regular and linear (R^2 = 0.6479) trend of pH reduction over time (y = -0.0231x + 5.5629).

The reduction in pH or the increase in acidity provides strong indications of the oxidative processes occurring in the insulating oil.

The pH can be correlated with the oil acidity, which measures the acidic components or contaminants of the oil [14], [30].

The acidity of a used oil results from the formation of acid oxidation products. Acids and other oxidation products will affect, together with water and solid contaminants, the dielectric and other properties of the oil. Acids influence the degradation of cellulosic materials and can also be responsible for the corrosion of metal parts of a transformer [14], [31].

The neutralization index or total acidity index (TAI) (NBR 14248) [32] is a test that provides information about the degree of oil aging.

Other tests are designed to analyze the polar compounds present in the oil. These tests are complementary to the neutralization index test since they indicate the quantity of polar compounds, i.e., compounds formed in intermediate stages of aging (e.g., peroxides and hydroperoxides) and more acidic compounds. These tests provide information about the existence of large quantities of intermediate compounds, which are on the way to forming acidic compounds, i.e., whether or not, despite a very high acidity value, we should change the frequency of the next sampling. Therefore, acidity provides an indication of the stage at which the oxidation process is [33-34].

Insulating mineral oil in service is subject to deterioration due to the conditions of use. The oil is subject to oxidation reactions due to the presence of oxygen, accelerated by high temperatures, and the presence of metals (iron, copper), acting as catalysts. Color changes, formation of acidic compounds and, in a more advanced stage of oxidation, sludge separation may occur. Electrical properties may be impaired [35].

C. *Conductivity:*

The range found for conductivity was 1.24 mS.cm^{-1} at the beginning of monitoring with a maximum of 3.42 mS.cm^{-1} and an average of 1.83 mS.cm^{-1} over the 54 days of oil evaluation. The graph shown in Figure 7 shows a weak (R^2=0.1844) trend of increasing conductivity over time ($y = 0.0113x + 1.5167$). The dissolved and ionized ions present in the oil transform it into an electrolyte capable of conducting electrical current.

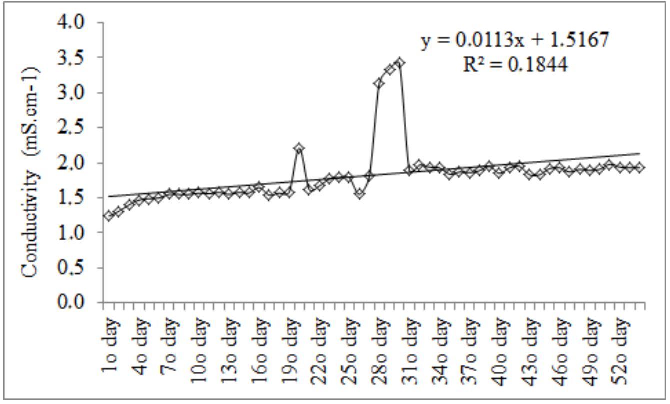

Fig. 7. Trend graph for conductivity (mS.cm-1).

Since there is a proportional relationship between the dissolved ion content and electrical conductivity, the ion content can be estimated by measuring the conductivity of an oil. The ions in the oil may be due to the presence of metals removed from the metallic components, mainly copper, zinc, nickel, and silver, which also act as catalysts. Given the high reactivity towards alkaline compounds and metals such as copper, the presence of oxygenated compounds must be taken into account [36].

The presence of metals also influences dielectric strength, as it indirectly measures the impurities contained in the oil, such as water, cellulose fibers, and particles (dust, metals, etc.) [37].

D. *Correlation between physical-chemical parameters:*

In the study of the correlations between the parameters evaluated (Table 2), significance less than 0.05 was found for all the correlations evaluated, which demonstrates that these parameters are interconnected as oil degradation occurs.

An excellent positive correlation was found between the DO and the color of the oil, while with the pH, the DO had a good negative correlation indicating an inverse relationship with the pH. Thus, with the increase in oxygen, there is the appearance of compounds that increase the acidity, hence the inverse relationship with the pH. The same does not occur with the color, which increases with the increase in the DO and consequently with the increase in the compounds that end up giving more color to the oil. By comparison, a darkening of the oil is noted as it degrades to more advanced stages of degradation where sludge appears.

TABLE 2. CORRELATION BETWEEN THE EVALUATED PARAMETERS.

	Color (mg.L^{-1} Pt-Co)	DO (mg.L^{-1})	pH	Conductivity (mS.cm^{-1})
Color (mg.L^{-1} Pt-Co)	1			
DO (mg.L^{-1})	p= -			
Significance	0.822	1		
pH	**p=0.000**	p= -		
Significance	-0.499	-0.714	1	
Conductivity (mS.cm^{-1})	**p=0.000**	**p=0.000**	p= -	
Significance	0.383	0.608	-0.556	1
DO (mg.L^{-1})	**p=0.004**	**p=0.000**	**p=0.000**	p= -

IN BOLD SIGNIFICANCE < 0.050.

A significant positive correlation was found between conductivity and dissolved oxygen (DO). In terms of color, oxidation promotes the appearance of dissolved ions, primarily due to the increase in acidity that results in the solubilization and migration of the transformer's metal components to the insulating oil. The study also revealed consistent negative correlations between pH and color, and between pH and conductivity, demonstrating that an increase in acidity (a decrease in pH) leads to a rise in these two parameters.

E. *Principal Component Analysis (PCA):*

Principal component analysis (PCA) is a dimensionality reduction and machine learning method used to simplify a large data set into a smaller set while maintaining meaningful patterns and trends.

The interpretation of principal components is based on identifying which variables are most strongly correlated with each component. These are the variables with the largest magnitudes, furthest from zero in either direction. For this work, a correlation above 0.7 was considered significant and is highlighted in bold in Table 3.

As seen in the correlation study and confirmed by PCA, all the chosen parameters are significant and have high factor loadings, emphasizing the correlation between color and DO, already verified by the correlation study.

TABLE3. FACTOR LOADINGS (UNROTATED)

	Factor 1	Factor 2	Factor 3	Factor 4
Color (mg.L^{-1} of Pt-Co)	**0.817**	0.522	0.167	-0.178
DO (mg.L^{-1})	**0.948**	0.171	0.032	0.266
pH	**-0.829**	0.203	0.516	0.079
Conductivity (mS.cm^{-1})	**0.746**	-0.565	0.350	-0.056
Expl.Var.	2.809	0.662	0.417	0.112
Prp.Totl	0.702	0.165	0.104	0.028

LOADS >0.700 ARE IN BOLD.

When calculating the eigenvalues, it was found that only factors 1 and 2 can explain 86.8% of the results, indicating a high similarity between the variables studied (Table 4).

TABLE 4. EIGENVALUES EXTRACTION: PRINCIPAL COMPONENTS

	Eigenvalue	% Total variance	Cumulative eigenvalue	% Cumulative eigenvalue
Factor 1	2.81	70.22	2.81	70.2
Factor 2	0.662	16.54	3.47	86.8
Factor 3	0.417	10.44	3.89	97.2
Factor 4	0.112	2.80	4.00	100.0

F. *Hierarchical Cluster Analysis (HCA):*

The study of correlations and PCA showed that the parameters with the best similarities (smallest bond distance) were DO and color. This correlation was confirmed in the HCA study. The most similar parameters indicate that the variation in DO influences the darkening of the oil (Figure 8).

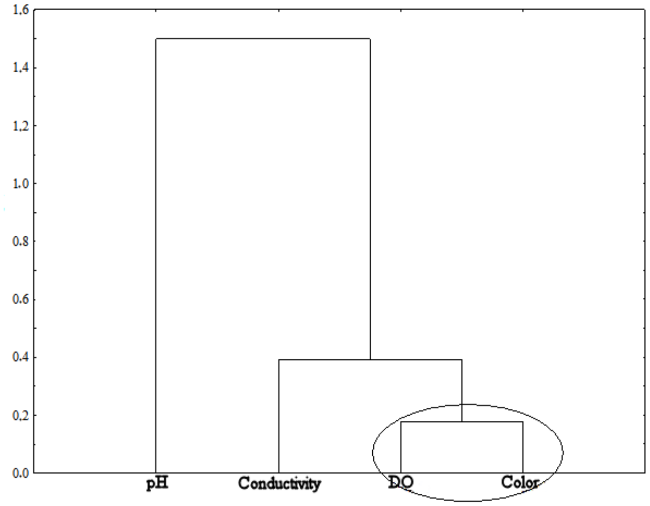

Fig. 8. Dendrogram of physical-chemical parameters. Simple link Pearson correlation.

IV. CONCLUSION

The proposed pilot system with automatic analysis of the parameters color, DO, pH, and conductivity met the initial proposed objectives of automating quality measurements of insulating mineral oil and can be optimized for use in high-voltage transformers. This facilitates the monitoring of oil degradation, saving time and increasing equipment safety.

The color and appearance of the insulating mineral oil were decisive in evaluating the oil's quality, with a considerable increase in values over time. From a clear, transparent, and clean oil, it changed from a light yellow to a dark color. The appearance of a dark metallic material was confirmed, which can be attributed to the increase in acidic compounds that may have dragged metallic components from the system itself. It can be deduced that the more yellow the oil, the greater the amount of sludge and consequently the greater the oxidation process of this oil. As the oil aged, its acidity, expressed by pH values, increased due to the probable presence of water and acidic contaminants during the observed period.

Regarding DO, variations with a tendency for its values to increase were observed. The probable presence of water content, due to the entry of humidity from the atmosphere of the Amazon region, may have been responsible for this effect. Conductivity increased over time, indicating that the capacity of the oil contained in the prototype, even in a simulation situation, changed. This increase may be due to dissolved water in the system.

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