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Development of a spectrofluorimetry-based device for determining the acetylene content in the oils of power transformers

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ABSTRACT

Power transformers are essential for a functioning electrical system and therefore require special attention by maintenance programs because a fault can harm both the company and society. The temperature inside a power transformer and the dissolved gases, which are primarily composed of acetylene, are the two main parameters monitored when detecting faults. This paper describes the development of a device for analyzing the acetylene content in insulating oil using spectrofluorimetry. Using this device introduces a new methodology for the maintaining and operating power transformers. The prototype is currently operating in a substation. The results presented by this system were satisfactory; when compared to chromatographic data, the errors did not exceed 15%. This prototype may be used to confirm the quality of an insulating oil sample to detect faults in power transformers.

1. Introduction

Electricity is currently an indispensable asset to society. Interruptions in the supply of electricity may cause political, economic, social and financial problems. The electricity distribution companies are responsible for delivering the energy produced by the generators to the final consumer. The generation typically occurs hundreds of miles from the distribution site; the resultant electricity is carried by transmission lines with nominal voltages on up to hundreds of thousands of volts. To convert this voltage to values suitable for distribution, power transformers are used. Power transformers are large equipment investments for plant distribution and are essential for a functioning electrical system [1]. Therefore, power transformers require special maintenance attention because a fault can harm both the company and society [2]. The temperature inside of a power transformer and the gases dissolved in the insulating oil are the two main parameters that are monitored [3,4].

One of the most important parts of a power transformer is its insulation system; this component is composed of solid cellulose impregnated with insulating mineral oil. The solid base may be paper, cardboard, cotton or wood. Mineral oil has two major purposes: dielectric and coolant [5]. As a dielectric material, the oil acts as an insulator, preventing electrical arcing within the transformer core. As a coolant, the oil dissipates the heat generated by the equipment during operation. The mineral oil is a fraction of petrol containing mainly hydrocarbons; its characteristics depend on the origin of the crude oil. Naphthenic mineral oil exhibits the best gas absorption. However, due to depletion of paraffinic mineral oil sources, this critical component is often recycled [6,7].

Even under normal conditions, the insulating system deteriorates, generating both combustible and non-combustible gases. The gas generation is more pronounced at higher temperatures. The gases are produced when the oil and other insulating materials, such as paper and cardboard core insulation, degrade. At 140 °C for example, carbon monoxide, carbon dioxide, hydrogen and methane are generated. At temperatures up to 500 °C, ethylene, ethane and methane are liberated. At extreme temperatures, such as during an electrical arc, hydrogen and acetylene are generated in addition to the previously mentioned gases. Using the DGA, it is possible to associate faults with the formation of some gases. These failures may be classified into three categories: partial discharge, heating and electrical arcs. The gases generated in the power transformer include the following: methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2). Other gases arise

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due to the natural degradation processes of the IMO; the principal components of these are nitrogen (N_2) and oxygen (O_2) [8].

The power transformers are designed for a long lifespan (approximately 20–25 years), but, can last up to 40 years under the correct procedures for operation and maintenance [9,10].

The standard procedure for monitoring power transformers and ensuring their longevity involves collecting samples of the semi-insulating mineral oil (IMO) for DGA (Dissolved Gas-in-oil Analysis). This method analyzes the types of gases, their concentrations and their rates of production in the transformer oil; these data can be associated with a type of fault [11].

There are several methods used to analyze DGA data; the most widely used technique in Brazil is NBR 7274 [12]. This technique is based on IEC 599 [13]. The NBR 7274 provides diagnosis based on the origins of the dissolved gases present in the IMO. The diagnosis is presented according to the data in Table 1, as adapted from [14].

Another important tool is the gas key. This method identifies the most significant gas for each failure [7].

The key gases associated with major faults are as follows:

- heating the oil: ethylene;
- heating the paper: oxide carbon;
- partial discharges: hydrogen; and
- electrical arcs: acetylene.

The DGA technique is not directly applicable on an operating transformer because the analysis is commonly performed using Gas Chromatography. In general, a sample is collected in the transformer and sent to a specialized laboratory; later, the client receives a report with the measurements and diagnosis. This process takes 5–9 days on average, depending on the location of the customer. Gas Chromatography is an analytical technique with high precision and accuracy. However, the distance between the substations and the laboratory, as well as the long intervals between the sampling and receiving the report/diagnosis lessen the analysis results' validity. Some equipment, including the Hydrangea [15], GMM [16] and Calisto [17] perform this process online.

However, these devices are expensive and most utility companies still send samples to distant laboratories.

To optimize and reduce the costs during the inspection process, this work describes the development of a portable device for analyzing the IMO in real time with remote access using spectrofluorimetry and a corresponding mathematical model to determine compliance automatically.

Due to the composition of the insulating oils and the importance of the acetylene gas concentration for diagnosing faults in power transformers, we envisioned using the fluorescence of these oils to predict the concentration of acetylene gas dissolved in an oil; this might be achieved by correlating the concentrations of acetylene with the fluorescence spectra of standard samples.

Table 1
Fault diagnosis according to NBR 7274.

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Diagnosis
< 0.1	0.1–1.0	< 1.0	Normal aging
< 0.1	< 0.1	< 1.0	Partial discharge of low energy
0.1–3.0	< 0.1	< 1.0	Partial discharge of high energy
> 0.1	0.1–1.0	> 1.0	Arc – discharge of low energy
0.1–3.0	0.1–1.0	> 3.0	Arc – discharge of high energy
< 0.1	0.1–1.0	1.0–3.0	Superheat ($T < 150$ °C)
< 0.1	> 1.0	< 1.0	Superheat (150 °C $< T <$ 300 °C)
< 0.1	> 1.0	1.0–3.0	Superheat (300 °C $< T <$ 700 °C)
< 0.1	> 1.0	> 3.0	Superheat ($T > 700$ °C)

Spectrofluorimetry is an important analytical technique used in laboratories and online systems in industry because the speed of the analysis, the sensitivity and the selectivity are high. Analyzing naturally fluorescent fluid allows samples to be prepared without additives.

2. Methodology

The methodology of this work consisted of performing Principal Component Analysis (PCA) using the fluorescence spectra of samples obtained in a LED spectrofluorimeter; the loadings and scores determined the best conditions for the filters, LEDs and photodiodes. The LED spectrofluorimeter was a Quimis Model Q-798FIL using a 1 cm quartz cuvette and one violet LED centered at 400 nm as the excitation source. The emission range was 335–1018.92 nm at 0.38 nm intervals. Through the partial least squares correlation between the fluorescence spectra of mineral oil samples with the concentrations of acetylene determined using chromatography as a reference method. After constructing the PLS model, predictions can be made using the properly calibrated acetylene concentrations in unknown samples.

After using PCA to determine the best conditions for the filters, LEDs and photodiodes, as well as verify the correlations between the fluorescence spectra of the samples and the concentration of acetylene measured via PLS, a bench prototype was subjected to 10 samples of IMO in three replicates, with known levels of acetylene. After the tests with bench prototype, a similar prototype was installed in the field.

3. Results and discussion

The PCA loadings helped determine the optimal conditions for determining the acetylene content (Figs. 1 and 2). Excitation using a blue LED generated emission detected at 522 nm. Therefore, we utilized an optical filter pass band centered at 522 nm.

Fig. 3 depicts the graph for the multivariate calibration (PLS) that reveals the predicted values versus the reference values using the fluorescence spectra as the independent variables and the concentrations of acetylene within 1–9 mg L^{-1} as dependent variables. The results agreed with those obtained by gas chromatographic analysis. The constructed models exhibited a high correlation between the real and predicted values. The correlation coefficient (0.9999) of the PLS model indicates that the model efficiently predicted the acetylene concentrations. The R^2 value

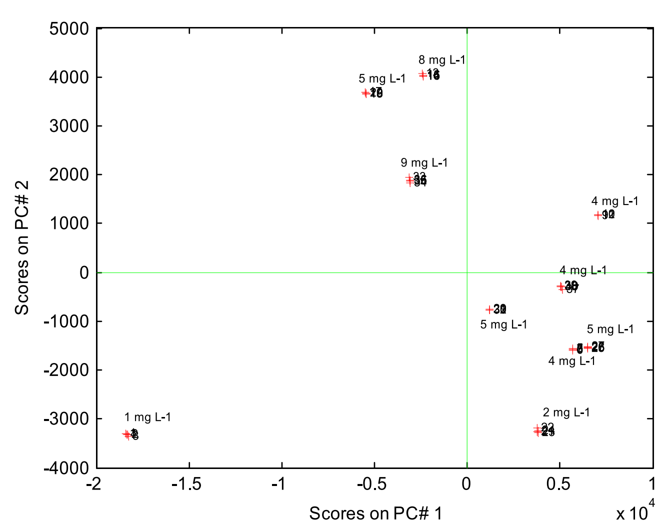


Fig. 1. Scores PC1 × PC2.

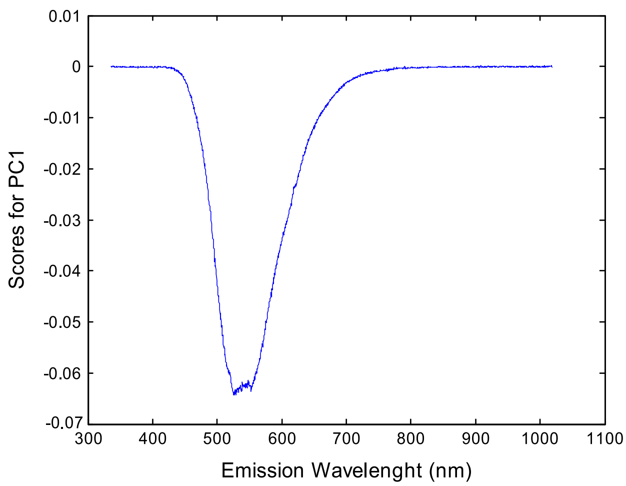


Fig. 2. Loadings on PC1.

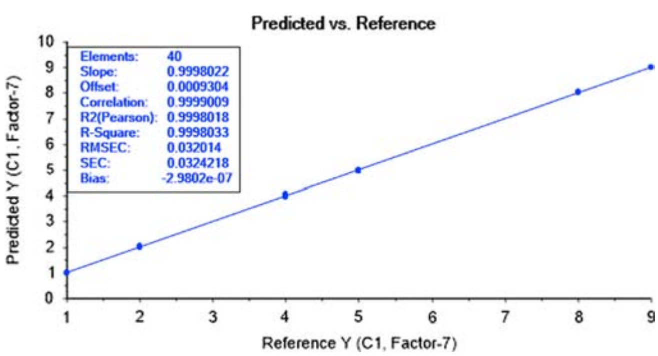


Fig. 3. Partial Least Square (PLS). Predicted versus reference.

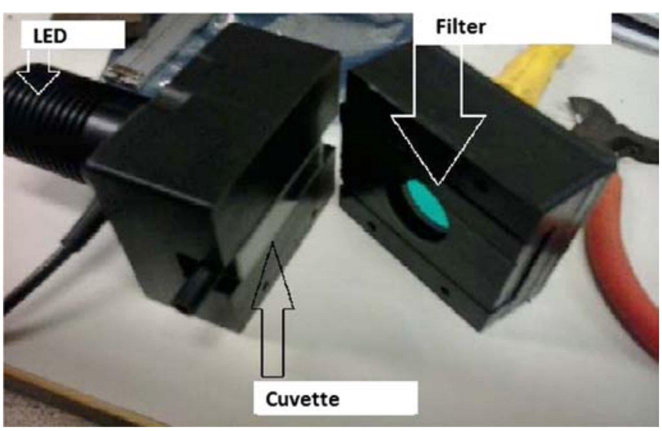


Fig. 4. Structure of the optical sensor for laboratory testing.

being near 1 indicates that the models accurately predicted the concentrations of acetylene in the mineral oil samples, revealing this technique's potential as a low-cost device for analyzing the acetylene content in power transformers.

The initial tests were performed using a bench prototype. The specific structures were assembled and 10 oil samples from operating power transformers with known acetylene levels were analyzed. Fig. 4 depicts the structure of the optical sensor used for laboratory tests.

Fig. 5 displays the graph built using the sensor's response during the laboratory tests for these samples. The *y*-axis represents the acetylene concentration (C_2H_2) (mg L^{-1}) obtained with the reference method (Gas chromatography) and the *x*-axis

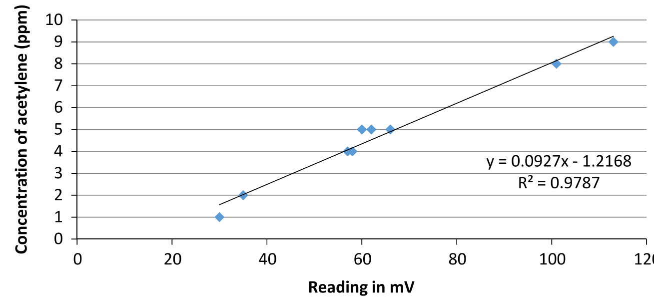


Fig. 5. Results of laboratory bench tests of the optical sensor.

reports the corresponding voltage (millivolts). The points are the actual sample values and the line represents the function used to interpolate the results. In Fig. 5, it is only possible to count 9 points because two samples contained equal values for their acetylene concentrations.

The prototype developed in this work contains four parts: the sensor unit, the data transmitter, the hydraulic unit and the control unit.

3.1. Sensor unit

This is the main part of the system. This unit is equipped with a sensor that measures the amount of acetylene dissolved in the oil based using spectrofluorimetry, specifically the samples' emission wavelengths. Fig. 6 illustrates the technical design of the optical sensor. The optical sensor utilized the incidence of light (excitation) in the oil storage device to emit other wavelengths (fluorescence) that are filtered using the optical filter. This process selects only for the characteristic wavelength of acetylene. It is possible to convert the analog signal to a digital one.

3.2. Data transmission unit

This unit transmits and receives information, as well as the control data. It is composed of a serial RS-232 interface, a GPRS modem and an antenna. Because the system uses a cell phone service, it is limited to locations with this type of service.

3.3. Hydraulic unit

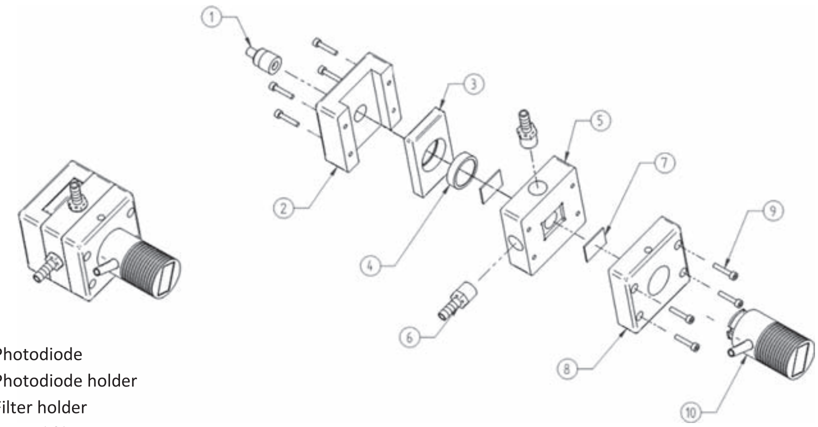
One of the problems encountered during the early development was renewing the oil inside the device. The solution required two items: one connects the outputs with different potentials (adapter) and a pump. The adapter, as illustrated in Fig. 8, has a 2" air inlet and two outputs for ¼" hose. The pump ensures that the oil flows from one outlet adapter to the other because they are at different potential levels.

3.4. Control unit

The control unit is responsible for the system's memory, as well as any decision-making, battery level backup checks, communication with other units and interfacing with the analog world. We utilized a PIC18LF2620 microcontroller to execute the algorithms.

3.5. Monitoring software

Software was developed to receive, interpret and analyze the information received by the sensor installed in a power transformer. The prototype communicates with the server using a GPRS modem; the information is processed and illustrated within the web interface of this monitoring software. The system is



1: Photodiode
2: Photodiode holder
3: Filter holder
4: Optical filter
5: Chamber for oil
6: Pintle of 1/4"
7: Glass slide with 21x16x1 mm
8: LED holder
10: LED

Fig. 6. Block Diagram – Sensor Unit.

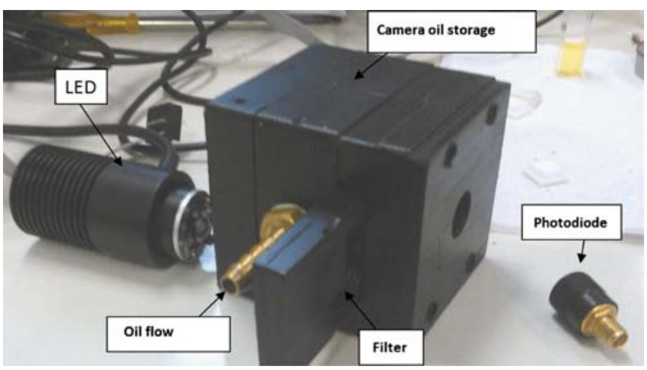


Fig. 7. Structure of the optical sensor.

Fig. 8. Adapter coupled to the valve 2".

Fig. 9. Photo of the prototype installed in field.

programmed to generate an alarm, when the acetylene concentration reaches a critical value (15 mg L^{-1}); however, this parameter varies between systems, making the dealership responsible for modifying the alarm limit. Using this software allows this new methodology for monitoring of power transformers to be distributed because the measurements for the gas concentration can be viewed remotely.

The difference between the bench prototype (Fig. 4) used during the laboratory tests and prototype installed in field (Figs. 6 and 7) is the use of a cuvette; using a cuvette precludes automatic sampling, making the system impractical for field analyses. The prototype developed for field use was installed in the transformer of a substation. The system's installation required 20 min and power supply for the control board came was the transformer itself. After installation, training was provided to the employees regarding the web interface Fig. 8. Fig. 9 depicts the equipment installed in the transformer. The last chromatographic analysis of the transformer indicated 2 mg L^{-1} acetylene was present, this integer value may have been rounded. Fig. 10 reveals the values read by the prototype using the mathematical function. In this version, no data were rounded.

The information from the embedded device arrived as code comprised of integer values from the analog/ digital converter (AD). For the acetylene concentration values, the linear equation found previously for samples with known concentrations was used (Fig. 5). $y=0.0927x-1.1268$

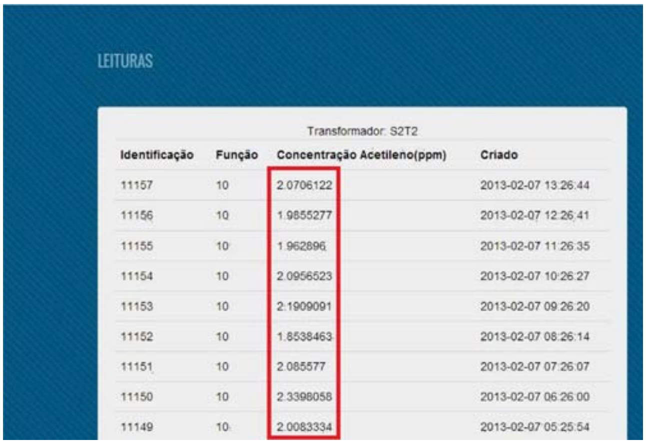


Fig. 10. Readings displayed in the web interface of the prototype.

4. Conclusions

Using this device introduces a new methodology for maintaining and operating power transformers and increases reliability of detecting incipient faults. The prototype may be used to confirm the quality of an insulating oil sample to detect faults in power transformers.

The prototype is currently operating in the field. The results presented by the system were satisfactory relatively to the last result; the chromatographic experiments revealed errors below 15%. When considering the average equipment readings and comparing them to the chromatographic data, the error was less than 3%; these values were notably close to those found during laboratory analyses.

This method is less expensive than gas chromatography or other analytical techniques, and its results can be obtained in situ.

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