Condition monitoring and diagnostic of large power transformers to improve its reliability and life cycle management

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Abstract— Power transformers are one of the most expensive elements of the power grid and in extreme cases a failure may result in their destruction. This represents a major cost for companies that manage this equipment and makes it imperative to detect defects at an early stage, so as to minimize damage. Therefore, it is vital to monitor and diagnose transformers continuously and automatically, not only to minimize damages associated with any defect of the transformer, but also to achieve a more efficient management of its life cycle.
A review to this continuous and automatic monitoring, which is essentially achieved through the use of sensors, and analyze transformer diagnostic methodologies, suggesting and demonstrating some strategies for that purpose, is made. A model is also developed. Despite still being in its initial stage, this model allows for a continuous assessment of the level of corrosion of tank walls.

Index Terms— **Power transformer, continuous monitoring and diagnostic**

I. Introduction

Power transformers are one of the most important elements of the electrical system as they allow for the adjustment of currents and voltages according to the existing needs. The use of transformers is therefore indispensable in the electric power transmission network due to the presence of the high voltages, which imposes the need to reduce the current circulating in power transportation lines in order to reduce losses due to the joule effect. This is mainly achieved by the use of step-up transformers at production output.
The unreliability of transformers not only affects the availability of electric power, but it can also lead to technical and economic losses, possibly with significant commercial and environmental consequences. This more than justifies the need for the detection and identification of failures already at their early stage so as to implement preventive actions, which is achieved mainly through a continuous monitoring of the transformer. In addition, if the condition of this equipment is continuously monitored in time, it is possible to manage the transformer’s life cycle. In other words, if the transformer is monitored continuously, it is possible to define maintenance actions based on the condition of this asset rather than providing preventive maintenance, which is nowadays the most common and is carried out at specific time intervals.

II. Oil-immersed power transformer: abnormal operating condition

Before monitoring and diagnosing a power transformer it is essential to understand the abnormal conditions it may be subject to. Thus, a brief description of the main components of the transformer and abnormal operating conditions is presented.

A. Active Part

1) Windings

The windings are usually made of copper and their function is to provide a path for the electrical current in the different phases of the transformer.
Abnormal operating conditions at the level of the windings are one of the most frequent causes of failures in transformers as they can be subject to mechanical (slackening, displacement or deformation), thermal ("*hot spots*" that sometimes lead to small cracks or even to the total breakdown of copper windings) and dielectric (dielectric disruption is due to the presence of high potential differences producing an electric field that causes rupture within the dielectric material) wear and tear [1]. These always appear coupled, and most often one of the phenomena has more impact on the onset of the failure. They generally lead to short circuits.

2) Transformer core

The transformer core is made of silicon steel laminations, a ferromagnetic material which combines a significant magnetic permeability with high mechanical resistance and allows the conduction of the magnetic flux with reduced magnetic dispersion and the reduction of swirling currents (eddy currents). Swirling currents are also reduced because of the laminated core structure, which enables a significant reduction of losses due to the Joule effect.
One of the most frequent defects seen appears in the core and is the displacement of its laminations due to electromagnetic forces. These can also be damaged by corrosion caused by chemical reactions between aged oil and the steel laminations. This leads to a loss of efficiency [1].

B. Insulation system

1) Solid insulation

Solid insulation is cellulose-based, namely paper and paperboard, impregnated with oil. Its function is to provide the dielectric and mechanical insulation of the winding. Abnormal operating conditions of this component result from the degradation of cellulose, which significantly contributes to the loss of dielectric and mechanical properties, which leads to short circuits between the windings, for example[2].

2) Liquid Insulation

The objective of the dielectric fluid is to isolate the transformer core and to cool the transformer by convection. The quality of the oil that is used greatly affects the properties of the insulation and cooling system, due to the appearance of particles (water, rust, acids) [2] in the fluid. These render the oil more viscous thus hampering its flow, thereby undermining the cooling capacity of the transformer. If these particles conduct electricity, short circuits may occur representing a failure of the insulation system [1].

C. Components and accessories

1) Bushings

Another type of abnormalities of transformers may occur in the crossings, which serve as an insulation between the passage from the outer conductors and the interior conductors that connect to the windings [3], in other words, they act as a path for the current of each phase through the walls of the tank.

The degradation of the bushings results mainly in the appearance of partial discharges and the loss of dielectric properties leading to their overheating. This degradation may be due to the following factors:

- Contamination of insulating material
- Presence of water
- Ageing of the bushing

2) Tap-changer

The tap changer is one of the most critical components of the transformer as it is one of the few moving parts. The tap changer is designed to adjust voltages and/or shift phases by varying the transformer's turns ratio without interrupting the load, thus allowing for the compensation of the constant load variations. A list of the most frequent abnormal conditions of tap changers that result in the inability to change turns ratio is presented below [1].

- Lack of maintenance
- Motor with old or burned condensers
- Springs of switches lose elasticity and may even break due to frequent use
- Wear and tear of the switching system
- Terminal carbonization

3) Tank

The tank contains the oil, and provides physical protection and support for the different components of the transformer besides ensuring the grounding of the magnetic circuit and the various metal parts. The tank may show cracks, essentially resulting from environmental wear and tear such as those resulting from corrosive environments, high humidity and solar radiation. The walls of the tank may also be subject to rupture due to high pressure gases resulting from internal arcs which vaporize the oil [4].

4) Cooling system

In power transformers, cooling is achieved through natural or forced circulation of oil and water or air. Forced circulation is based on the use of pumps and fans.

The most significant abnormalities of the cooling system lead to the increase of the temperature of the oil of the transformer, which affects the different components of the transformer and can even lead to the increase of the pressure of the gases formed, resulting in the explosion of the transformer. These failures may, for example, be caused by cracks in the tubes where oil circulates (causing the reduction of the amount of oil leading to decreased heat exchange), or even due to anomalies in fans due to erroneous measurements of the thermometers or the malfunctioning of the ventilation and pumping system[1].

III. Traditional Methods for Diagnosing Power Transformers

This section reviews the traditional methods for diagnosing power transformers, so as to understand which methods are used to diagnose the situation of each component.

A. Dissolved gas-in-oil analysis

A defective transformer produces gases, the two main results of this being electrical disturbances and thermal decomposition. The rate at which each of the gases is produced depends essentially on the temperature and to a lesser extent on the volume of material. The main gases involved in the faulty transformers are: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2).

The total concentrations of gases, their relative proportions and the rate of increase of each gas allow us to access the status of the transformer. There are several criteria that may be used to associate these parameters with the type of failure that occurred, the most common being the Rogers method, Doernenburg, IEC 60599, Duval, Key Gas and TDCG. All of these criteria are empirical and results are based on the correlation between the gases detected, that is, many of these use ratios to determine a failure, a fact that allows for the elimination of the effect of the oil volume and some sampling effects. Some of the most well-known ratios and possible associated fault types are also presented below [5]. It should be noted that these are only meaningful and should only be calculated if at least one of the gases exceeds its typical concentration and growth rate.

R1: (CH_4/H_2) – Partial discharge
R2: (C_2H_2/C_2H_4) – Electric arch
R3: (C_2H_2/CH_4)
R4: (C_2H_6/C_2H_2) – High intensity discharge
R5: (C_2H_4/C_2H_6) – Oil overheating > 500 ºC
R6: (CO_2/CO) – Cellulose overheating
R7: (N_2/O_2) – Oxygen consumption; sealing

B. Oil quality

Several oil tests are conducted to check the state of contamination and deterioration as well as their electrical properties. Electrical, physical and chemical testing is performed (dielectric strength, power factor, interfacial tension, color, sludge and sediments, acidity index, relative humidity, kinematic viscosity and particle content, etc.) [7].

C. Degree of polymerization

The degree of polymerization is defined as the number of glucose rings present in a cellulose macromolecule and provides an indication of the state of the paper and of the mechanical strength of the insulation system. This can be measured indirectly via an analysis of furan compounds or directly by means of paper samples. The Arrhenius equation (eq. 1) is used to estimate the degree of polymerization (DP) at a given time after its initial measurement [6]. It depends of activation energy (E_a), chemical environment (A), hotspot temperature (T) and gas constant (R).

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = A.e^{-\frac{E_a}{R.T}}.t \qquad (1)$$

D. Frequency response analysis

By analyzing the response frequency of the transformer it is possible to detect any possible deformation of the windings when compared to a previously obtained reference [6].

E. Power factor

The power factor refers to the ratio between the leak current of the resistive component and the capacitive component, resulting from the application of an alternating voltage. This test is used to determine the condition of the insulation between windings and magazines, and it only provides an indication of the general state of the insulation system [6].

F. Excitation current

Measuring the excitation current through a test in open circuit identifies faults in the magnetic circuit and windings of single-phase or three-phase transformers, such as, for example, short circuited or open windings, problems in the voltage regulator and bad electrical connections. Test results should be compared with previous tests or with other phases (for three-phase transformers) [6],[7].

G. Leakage reactance

Also known as the short-circuit test, the measurement of leakage inductance is a traditional method used to detect changes in the geometry of the windings and the core. These deformations change the magnetic flux and hence leakage inductance. Values obtained are compared with information from the rating plate, previous tests or with tests performed on similar transformers [6].

H. Insulation resistance

This test is a usual one. However, it is not standardized due to the variability of results that depends on the environmental parameters at the time of measurement (temperature, humidity, level of impurities present in the insulation material). The insulation resistance provides information on the status of the insulation [6].

I. Winding resistance

The electrical resistance of each winding is measured with direct current. It is necessary to measure and record the temperature associated with each resistance measurement, as a change in temperature implies a change in resistance. This test indicates the state of the windings and of the voltage switch. A variation of 5% or more from the rating plate data is a synonym of serious damage to the conductor [6].

J. Partial discharges

The partial discharge test is essentially qualitative. Partial discharges result from local dielectric disruptions of the insulation system. The intensity and frequency of partial discharges are a good indicator of the state of the insulation material, as these increase with its corrosion and decomposition. In order to have a good perception of their location, both the acoustic and electrical signals should be measured. At present, there are already several models of continuous monitoring equipment based on the measurement of these two variables [6].

K. Turns ratio

Turns are subject to electrical and mechanical wear, which may result in short circuits or open circuits. The ratio of turns (N2/N1) is related to the ratio between secondary voltage (V2) and primary voltage (V1), that is, $V2/V1 \approx N2/N1$. The ratio between turns should not differ more than 0.5% of the ratio of the nominal voltages of the windings, indicated on the rating plate.

L. Return voltage and polarization currents

The return voltage method provides access to the water content and to the level of degradation of the insulation system.

By analyzing the response frequency of polarization and depolarization currents it is also possible to understand the condition of the insulating material [6].

M. Mechanical vibrations

Transformer mechanical vibrations originate in the core, where they are induced due to the change of the magnetic field, and in the windings, induced by electromagnetic force.

To measure these vibrations sensors are installed (accelerometers) on the sides and top of the transformer vat. Signals obtained are usually transmitted through an optical isolator and registered on a specific device. Through these signals it is possible to detect the condition of the windings and of the magnetic circuit [6].

N. Temperature and infra-red test

Transformer load capacity is limited by the temperature of the windings (which is not uniform). The traditional method for estimating the temperature of the windings is to measure it at the top and base of the vat. The real limiting factor is the hot-spot, which is located at the top of the transformer and is not directly accessible. Sensors have been developed to measure the temperature of the hot-spot of the windings directly, the most reliable of them appearing to be optical fiber ones. These sensors are placed in spacers or in the conductors that are to be monitored. According to IEC, hotspot temperature should not exceed 98 ºC.

Infrared testing can locate hot areas which are at a temperature above that of the outer surface of the transformer. The test results in a four-color thermal image which is white, red, blue and black. The hottest areas are displayed in white and red whereas colder areas are displayed in black and blue [6],[7].

O. Bushings condition

As bushings are in contact with the exterior they are subject to greater deterioration and are more vulnerable to accidents involving the exterior of the transformer. The techniques used to monitor bushings are adaptations of the aforementioned ones (analysis of gases dissolved in oil, oil quality, partial discharge, infrared thermography, power factor, temperature, etc.) [6].

P. Tap-changer condition

The monitoring of this type of devices is critical and is most frequently carried out by temperature analysis, dynamic and static resistance to windings, motor supply current which triggers the switch, gases dissolved in oil and vibrations [6].

IV. ONLINE DIAGNOSTIC MODELS FOR POWER TRANSFORMERS

In this section there are presented the diagnostic models based in online data, which are adaptations of methodologies shown in section 3.

A. Thermal model

It's essential monitoring temperature, mainly hotspot temperature, in order to increase operation efficiency and reduce the probability of stopping power transformer. Other important measure is topoil temperature. It's possible to measure hotspot temperature directly using optical fiber or indirectly applying models that estimate it.

Standard IEC 600767-7 suggests a thermal model based on ambient temperature, load factor and characteristic parameters of transformer. These parameters depends on cooling type, so it's also necessary to record the cooling type of transformer at each moment of measuring so that the parameters change according it. Example of computation using difference equations is presented in standard, where is important to highlight the fact that inputs time step has to be less than half of winding time constant.

B. Water content in paper model

There are several methods to access to the water content in paper, and they can be direct or indirect. There is only one direct method consisting in the extraction of a piece of paper and a measurement by Karl Fischer titration. Indirect methods are based for example in a measure of water content in oil, or power factor measurements or dielectric resistance measurements.

As the most usual is the one based in a measure of water content in oil this one will be focused. Application of this method consist on a measure by Karl Fischer titration and the estimation of water content in paper (%) using equilibrium curves (ex: Oomen equilibrium curves) or equations (ex: Fessler equation).

This curves and equations are only valid when thermodynamic equilibrium is achieved, which in practice never occurs. So, in order to minimize the error a long term average is required. It's proved that a seven days average give a good precision of water content in paper for that seven days [9].

To compute water content in paper (WCP (%)), Fessler equation is applied (eq. (2)) [8].

$$WCP = 2.173 \times 10^{-7} \times p^{0.6685} \times e^{\frac{4725.6}{T+273.15}} \quad (2)$$

To apply equation (2) is necessary to compute first water vapor pressure (p), which, assuming equilibrium, can be estimated using eq. (3) and depends on water content in oil (WCO (ppm)), solubility of water in oil (Ws) and saturation water vapor pressure (p_s).

$$p = \frac{WCO}{Ws} . \mathrm{p_s} \quad (3)$$

Saturation water vapor pressure can be estimated by eq. (4) [8].

$$p_S = 0{,}00603. e^{\frac{17{,}502 \times T}{240{,}97+T}} \quad (4)$$

Solubility of water in oil is computed using eq. (5), where A and B are variables that depend on oil condition, in [5] it's suggested that B takes the value 1567 and A the value 7.0895.

$$W_S = 10^{-\frac{B}{T+273{,}15}+A} \quad (5)$$

For eq. (5) temperature (T) should be representative of the local of measurement of water content in oil. The other equations (eq. (2), (3) and (4)) should take the temperature (T) representative of the local of paper that it's intended to estimate water content in paper.

In [5] is also suggested the limits for water content in paper presented above.

- <69 kV, 3% maximum
- 69 kV-230kV, 2% maximum
- >230 kV, 1,25% maximum

Having the value of water content is possible to estimate the temperature for what risk of bubbles formation exists. The estimation is achieved using eq. (6) [9], which use two parameters that depend of material (A and B, this ones are different for the ones of eq. (5)). Values for A and B are suggested in [10].

$$T = A. e^{B.WCP} \quad (6)$$

C. Ageing model

Ageing model has the purpose of estimate the condition of paper along the time, being of enormous utility because there's no direct access to paper. The estimation of the condition of paper is done computing the degree of polymerization, using eq. (1). Where activation energy (E_a) takes as usual value 111 kJ/mol, the constant that depends of chemical environment (A) varies with water content, oxygen concentration and acidity (with minor relevance). In [11] it was determined the value of A for environments with low, medium and high oxygen concentration and for 0.5%, 1.6% and 2.7%, using or kraft paper or thermally upgraded kraft paper. Doing a polynomial interpolation as in [12] for equations (7), (8) and (9) is possible to define all the equations for compute A constant, the equations are presented below, from eq. (7) to eq. (12).

So it´s possible to refresh the estimation of the degree of polymerization according the time step of temperature, water content in paper and oxygen concentration.

Kraft paper:

- Low oxygen content in oil (<6000 ppm):

$$A = 1{,}78.10^{12}.wcp^2 - 1{,}10.10^{10}.wcp + 5{,}28.10^7 \quad (7)$$

- Medium oxygen content in oil (7000 ppm-14000ppm):

$$A = 1.30.10^{11}.wcp - 1.84.10^{8} \quad (8)$$

-High oxygen content in oil (16500 ppm-25000ppm):

$$A = 1.71.10^{11}.wcp + 1.55.10^{8} \quad (9)$$

Thermally upgraded kraft paper:

- Low oxygen content in oil (<6000 ppm):

$$A = 2{,}26281.10^{12}.wcp^{2} - 2{,}9119.10^{10} * wcp + 1{,}56625.10^{8} \quad (10)$$

- Medium oxygen content in oil (7000 ppm-14000ppm):

$$A = 3{,}13223.10^{12}wcp^{2} - 1{,}7686.10^{10}.wcp + 2{,}13124.10^{8} \quad (11)$$

- High oxygen content in oil (16500 ppm-25000ppm):

$$A = 2{,}6405.10^{12}.wcp^{2} + 9{,}0095.10^{10}.\mathrm{wcp} - 8{,}74876.10^{8} \quad (12)$$

D. Load model

Load model consists in verifying the load factor value along the time, since it shouldn't be above 200 % of nominal value. So, ever it is above 200% an alarm should sound, and a check to other components condition must be done.

E. Dissolved gas-in-oil analysis model

This model consists on the application of the methods of dissolved gas-in-oil analysis described in 3.1. As referred previously the application of the methods are only valid when the concentration of gases and its rate of change is above certain limits. On table 1 are presented limits for concentration of gases according some entities with more relevance [13].
Limits for rate of change, according to IEC standard 60599-1999, depends a lot of power transformer, age, type of identifiable faults, load patterns and insulation volume. Standard suggest that an increase of 10 % per month generally is representative of an active fault, and if there's no change or change is very low means that probably the fault is extinct. So the methods of dissolved gas-in-oil analysis only are applied if the concentration above the specified limit and the rate of change is above 10 % comparing to the day 30 previous the day in analysis.

Table 1 – Limits for concentration of dissolved gases-in-oil [12]

<table>
<tr><th></th><th colspan="8">Gas concentration (ppm)</th></tr>
<tr><th></th><th>H_2</th><th>CO</th><th>CO_2</th><th>CH_4</th><th>C_2H_6</th><th>C_2H_4</th><th>C_2H_2</th><th>TCG</th></tr>
<tr><td>IEC 60599-97</td><td>60-150</td><td>540-900</td><td>5100-13000</td><td>40-110</td><td>50-90</td><td>60-280</td><td>3-50</td><td></td></tr>
<tr><td rowspan="2">Cigre 15.01</td><td rowspan="2">100</td><td colspan="2" rowspan="2">Σ CO+CO2 < 10000</td><td></td><td></td><td></td><td>20</td><td></td></tr>
<tr><td colspan="4">Σ C_nH_y < 500</td><td></td></tr>
<tr><td>IEEE Std C57,104-91</td><td>100</td><td>350</td><td>2500</td><td>120</td><td>65</td><td>50</td><td>1</td><td>720</td></tr>
<tr><td>Laborelec</td><td>200</td><td></td><td></td><td colspan="4">Σ C_nH_y < 300</td><td></td></tr>
</table>

F. Bushing model

Bushing model consists on measuring capacitance C and power factor (cos θ), this measurements can detect abnormal operating conditions that arise in bushings and are of simple interpretation.
For continuous measurement of C and cos θ values a sensor is installed at capacitive tap, which allows the connection of test equipment. Suggested limits for both are suggested in IEEE standard C57.19.01-2000.

G. Tap-changer model

The monitoring and diagnostic of tap-changer is done by measurements and analysis of mechanical vibrations, tap-changer oil temperature and motor current. Along with these three measurements, it is vital to know in what position tap-changer is because it permits to have an idea of what position can be faulty.

H. Tank model

In the tank there is a lack of online monitoring and diagnostic models, and to determine its condition the traditional method consists in visual examination. As such, it was developed a model that is in a beginning phase, which allows access to the level of depth corrosion (detecting oil leaks) depending on the material's resistance to corrosion. It should be noted that the corrosion resistance of the material depends on factors such as the material itself, the temperature, the acidity of the solution, oxygen, moisture and chemical salts. In the corrosion model it is intended that the influence that these factors have on corrosion resistance are accounted continuously, in order to be able to estimate when can or not exist oil leak. It is also intended to add to model surface corrosion, so it's possible to have an overall perception of the condition of the tank.
In the model it is assumed depth corrosion as a stochastic process, i.e. its assumed depth of corroded metal as a random variable that changes over time and its variation is related to metal corrosion resistance which also varies over time. The model was developed in the NetLogo program, and is based on existing percolation models in the library of the same, more precisely the model "Infiltration Oil in Porous Soils". Fig. 1 shows a simulation where it was verified that corrosion does not fully pierced the wall, i.e. there is no oil leak.

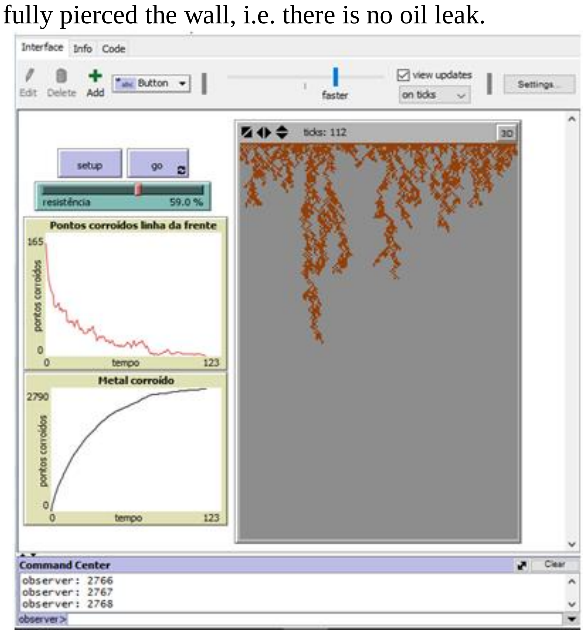

Fig. 1 – Simulation done on NetLogo where corrosion doesn't pierced

the wall.

Fig. 2 shows the variation of the number of points corroded as function of the corrosion resistance. For this graph it was carried out a simulation for each resistance value between 0% and 100% with a step of 2,5%, it is found that 57,5% represents the corrosion threshold. That is, when corrosion resistance is close to 57,5% there is a risk of occurrence of oil leak

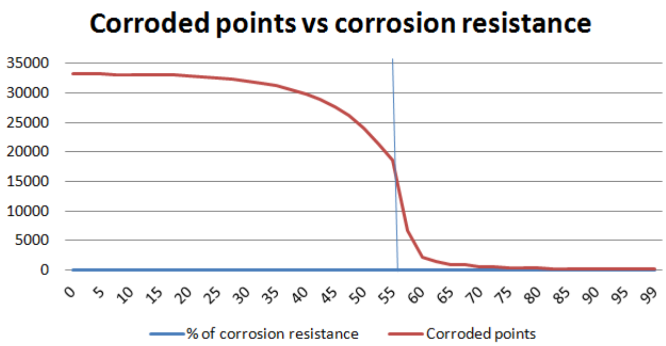

Fig. 2 – Number of corroded points as function of corrosion resistance

I. Cooling system model

Monitoring of cooling system is based on comparing the measured temperatures of the hot-spot and top oil with temperatures estimated by the thermal model. Knowing what type of cooling that the transformer is every moment is possible to estimate the temperature of the hot-spot and top oil by thermal model and compare it with the measured temperatures. If temperatures are too disparate, probably means that the cooling system will not be operating normally.

V. Transformer TR1

Transformer TR1 is a phase-shifter transformer with a power rating of 1400 MVA. This one has installed a multi-gas-sensor which measures the concentrations of C2H2, C2H4, H2, CO and H2O in oil. For which there are two sampling periods separated by approximately 2 months, these gases and water was converted to a daily time base and there concentrations were corrected when values corresponds to impossible measurements. Active power, reactive power, apparent power, primary and secondary voltages, tap position and a temperature (which the location is unknown) are also measured continuously in time (online), these ones are only available in the first period of online measurements and are in a time base of 2 in 2 minutes.

Offline reports, which are assumed to be the measures taken from specialized people and spaced in time, are also available. The measured quantities are the concentrations of H_2, O_2, N_2, CO, CO_2, CH_4, C_2H_4, C_2H_6, C_2H_2, H_2O and furan in the oil, some oil quality measurements and bottom oil temperature at the time of measurement. There's no sampling pattern for offline variables.

A. Load factor

The load factor results from the division of current by the nominal current. In the absence of measured current values, this was obtained by the relation of this with the voltage (U) and apparent power (S), the equation expressing this relationship is presented below.

$$I = \frac{S}{\sqrt{3}.U} \tag{13}$$

The voltage has an approximately constant value over time, while the apparent power varies greatly and switches between negative and positive values, corresponding to the fact that the energy transit is done to one side or the other. It was observed that in most cases the load factor is similar during the weekdays (monday to friday) and different from these during the weekend (saturday and sunday), and although there is a seasonality in the patterns.

B. Temperature

For the online temperature location is unknown, however it is believed is representative of the windings. In order to prove this, a comparison of online temperature with load factor is done, the result appears in the fig. 3, where it's possible to see that the temperature variation is similar, even with a small delay, to load factor variation, that is, this temperature is representative of some place in power transformer.

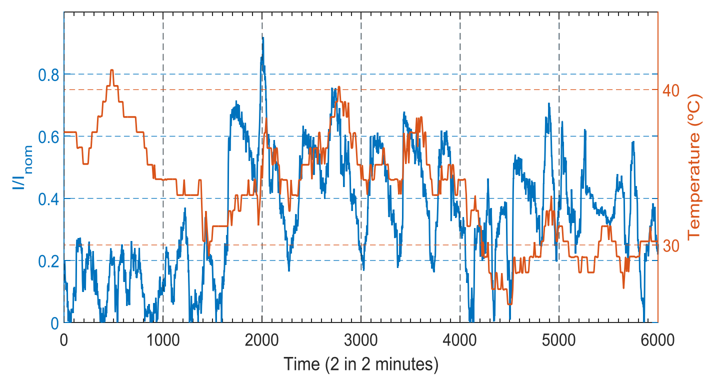

Fig. 3 – Evolution of load factor (blue) and temperature (orange)

It was verified that for almost all days on which exists online and offline measurements, the online temperature ("supposed" as windings temperature) is below offline temperature (bottom oil temperature), as is shown in fig. 4. So online temperature can't be representative of windings temperature.

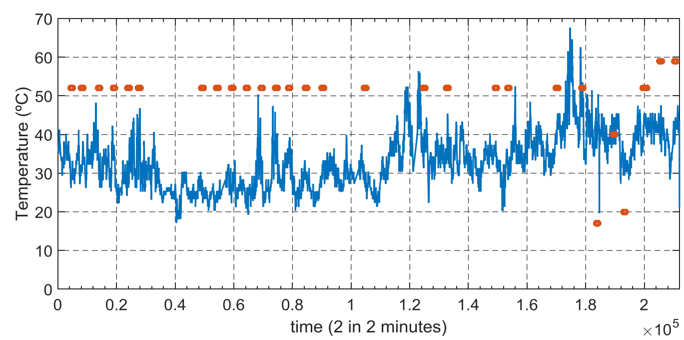

Fig. 4 – Evolution of online temperature (blue) and offline temperature (orange)

C. Tap-changer position

The registration of the tap-changer position is very important to determine the state of the same, so can be realized which tap will be with more wear, allows also to calculate averages of switching's or associated with other records, such as mechanical vibrations, permits understand what tap or taps will be probably with problems. The following figure (fig. 5) shows the number of times each tap was switched, it is clear that zero is the one that has a greater number of switching's as such would be expected to present a greater wear, followed by tap ten that also presents a high number of switching's. It was also found that there is no daily or seasonal pattern for the tap-changer positions.

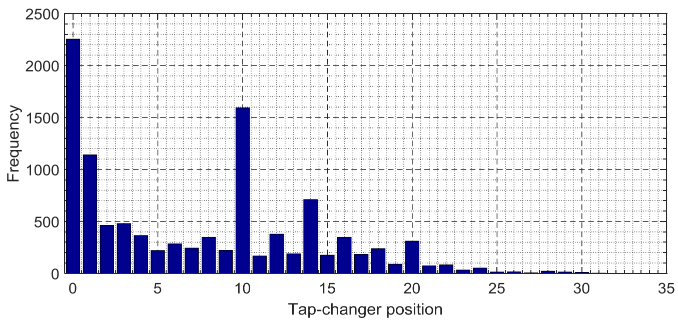

Fig. 5 – Frequency of tap-changer positions

D. Gases

The figures below represent the evolution of concentrations of online gases (blue) and offline gases (orange). Fig. 6 shows the evolution of acetylene, which is shown, although high, stable.

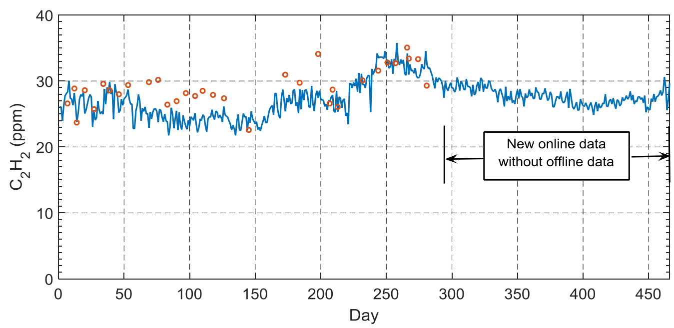

Fig. 6 – Evolution of acetylene in online (blue) and offline (orange)

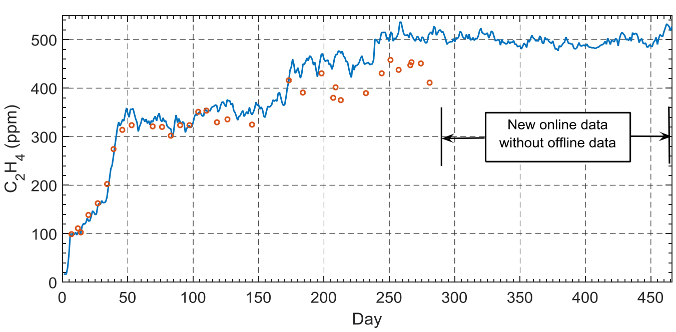

Fig. 7 – Evolution of ethylene in online (blue) and offline (orange)

In Fig. 7 it's possible to visualize the evolution of ethylene, which has three distinct zones, in the first (between day 0 and approx. day 50) the growth is very pronounced, in the second (between approx. day 50 and day 250) growth is lower and in the third (from approx. 250 on and the weekend) concentration stabilizes.

In Fig. 8 is presented the evolution of the concentration of hydrogen, which shows a high increase at the beginning and then stabilizes. It is observed an offset between online data (blue) and offline data (orange) of approximately 40 ppm.

The evolution of carbon monoxide is presented in Fig. 9, where it is found that growth is approximately constant.

Observing the figures prove that the gas measured by the sensor (online) and gases measured by specialists (offline) are quite near on days which there are data of both and have the same trend.

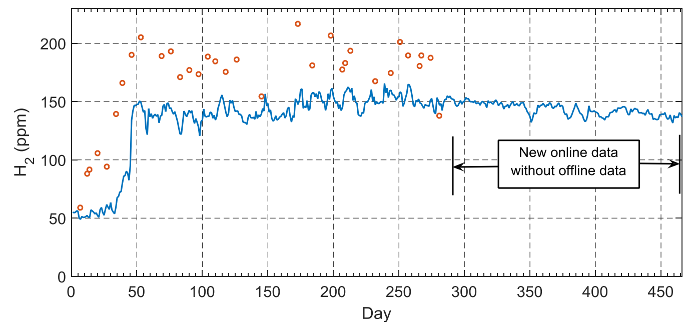

Fig. 8 – Evolution of hydrogen in online (blue) and offline (orange)

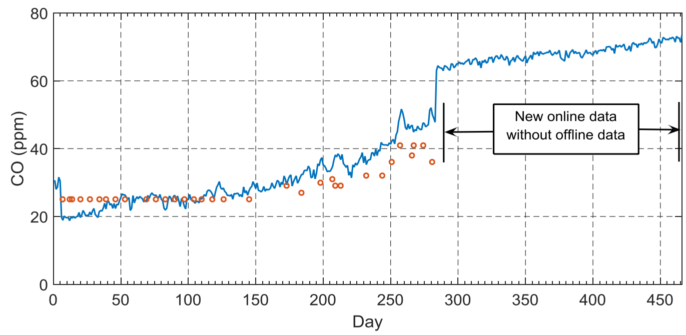

Fig. 9 – Evolution of carbon monoxide in online (blue) and offline (orange)

The following table (table 2) presents the differences between the online and offline data for the days when there are both measurements, as it's possible to see that for acetylene and monoxide carbon both root mean squared error, absolute mean error and relative mean error are low and this deviation can be explained by the uncertainty on measurements. For ethylene besides the relative mean error is low the other two errors have to be considered significant (representing the discrepancy observed after aprox. day 180). For hydrogen as visualized there is a general offset of approximately 40 ppm proven by the errors.

Table 2 – Errors between gases measured in online and offline for dates where both are measured

Gás	**RMSE (root mean squared error)**	**AME (absolute mean error)**	**RME (relative mean error)**
C_2H_2	3,07 ppm	2,35 ppm	8,01%
C_2H_4	45,93 ppm	34,77 ppm	9,6%
H_2	43,93 ppm	40,22 ppm	25,0%
CO	5,48 ppm	4,45 ppm	14,91%

E. Water

In order to be able to compare the results of online and offline measurement of water is necessary to put water content in the oil in the same reference temperature. To fix water values to the same reference equation (14) is applied.

$$WCO(20ºC) = \mathrm{WCO(T)}.2{,}24.\mathrm{e}^{-0{,}04.\mathrm{T}} \quad (14)$$

It can be seen in Fig. 10 that there is a discrepancy between the online (blue) and offline (orange) data for water content in oil measurements. This discrepancy can be explained by the fact that temperatures online and offline may not represent the same location of power transformer or due to the uncertainties in the measurements both online and offline.

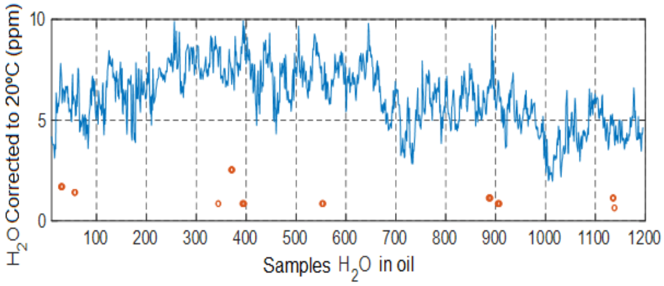

Fig. 10 – Samples of water content in oil corrected to 20ºC for online (blue) and offline (orange)

VI. Transformer TR1: continuous and diagnostic models

In this section, models described in section IV that have data available are applied.

A. 6.1 Thermal model

This model has as inputs the ambient temperature and the load factor. It's also necessary define the parameters of the model related with characteristics of power transformer. Since the only information about type of cooling is that it's "ONAF", the parameters are the ones suggested in IEC 600767-7 for this type of cooling. In order to apply the model, load factor and ambient temperature have to be available with a time step less than 3.5 minutes, which is half of winding time constant. Load factor is available with a time step of 2 minutes, what respects the condition described above.

Ambient temperature isn't available so it's necessary to get it. Site https://www.wunderground.com permits to get historical climacteric information easily, this information is in a daily time base, for example, minimum, maximum or mean ambient temperature. Other variables are also available like wind, precipitation, dew point, etc. As ambient temperature has to be in a time base equal to load factor is necessary to estimate it. In [14] some models that permit estimate daily ambient temperature cycle are suggested, where "wave" is simple and the one that gives minor root mean squared error. The inputs of this model are minimum and maximum ambient temperature and the sunrise hour.

For the time period that there is data from power transformer, the closer climacteric station that has ambient temperature available is about 25 km distance from TR1. So in order to apply thermal model is necessary to show that the daily ambient temperature cycle estimation by model "wave" leads to hotspot and topoil temperatures similar to the ones that use measures of ambient temperature.

It was found that for more recent periods of time (since 2016) there are available hourly ambient temperature measures in a climacteric station at about 5 km distance of TR1. In fig. 11 is shown the estimation of hotspot with ambient temperature simulated (orange) and measured (blue) for one week in January. The load factor data used in these estimations corresponds to one random week of online data.

To reinforce the validity of the simulation of ambient temperature it was done the same as above but for one week in August. The errors between hotspot temperature using ambient temperature simulated and measured are presented in table 3, where it's possible to verify that the error is minimum. It should be noted that the error committed is equal for topoil and hotspot temperatures.

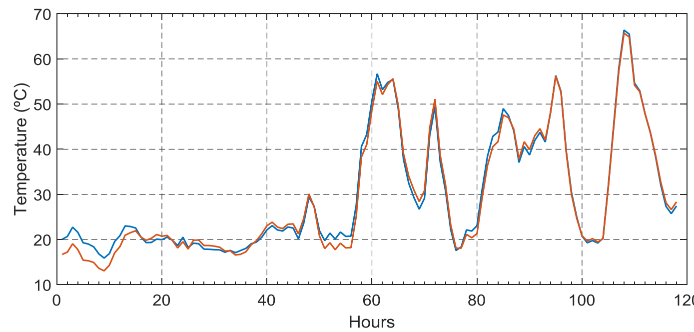

Fig. 11 – Evolution of hotspot temperature for one week in January using simulated (orange) and measured (blue) ambient temperatures

Table 3 – Errors for hotspot and topoil temperatures estimated with simulated temperature and measured temperature

	January	**August**
RMSE	1,51ºC	2,17ºC
AME	1,16ºC	1,54ºC
RME	4,79%	3,74%

Next figure (fig. 12) presents the evolution of the estimation of hotspot (yellow) and topoil (orange) temperatures and the temperature available on online data (blue) for the first 400 hours of sampling. As can be seen the amplitude of variation of temperature available on online data is very low compared with the other two, reinforcing again the idea that this not representative of winding temperature. However it's possible to verify that the variation follows the same pattern.

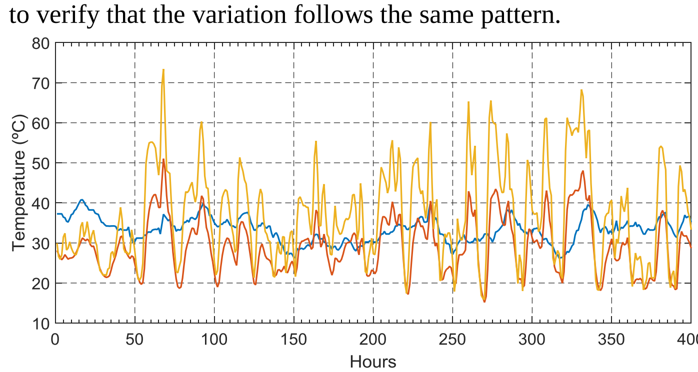

Fig. 12 – Evolution of estimated hotspot(yellow) and topoil(orange) temperatures and temperature available on online data (blue) for the first 400 hours of sampling

B. *Water content in paper model*

The computation of the water content in paper requires measures of water content in oil, temperature of the local where water is measure and temperature representative of the local of paper where the water content is pretended to be estimated. Although the local that temperature of online data represents is unknown, it seems to have a variation similar to water content in oil, so it's assumed that this temperature is representative of local of measure.

The temperature of the local of paper where the water content is pretended to be estimated is the topoil temperature estimated by thermal model, since it's in contact with paper at the top.

So using equations (2)-(5) water content in paper can be estimated, in fig. 13 is presented the water content in paper (blue), it seven days mean (black) and means of water content in paper pondering last seven days (orange).

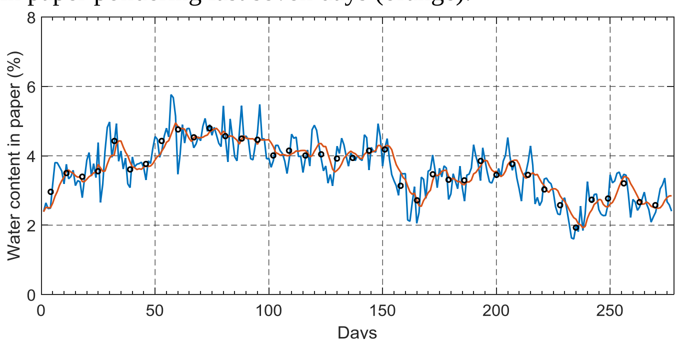

Fig. 13 – Evolution of water content in paper (blue), seven days mean (black) and mean pondering last seven days (orange)

It appears that both the seven days average and the average weighting the last seven days follow the same trend so it is possible to use the average weighting the last seven days and have a daily value of water content in paper. The value of water content in paper exceeds always the suggested limit of 1.25%, indicating excess of water in paper, however there's no certain in these values because of the difference in water content in oil for online and offline data. Having water content in paper it's possible to estimate the temperature for what there's a risk of formation of water bubbles, which is displayed in fig.14 with the blue color, hotspot temperature is also represented with orange color. As can be seen hotspot temperature never go close to temperature of bubbles.

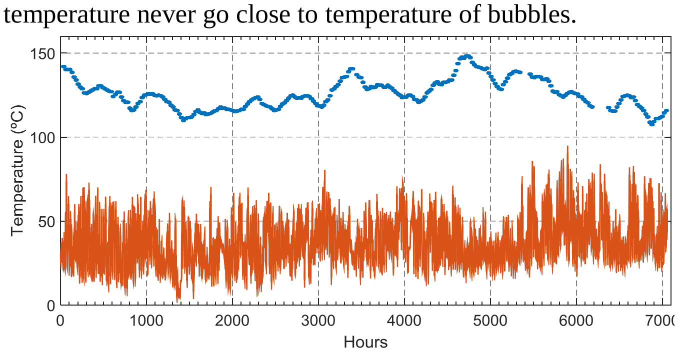

Fig. 14 – Evolution of temperature for risk of bubbles formation (blue) and hotspot temperature (blue)

C. *Ageing model*

For the aging model it is necessary to have as inputs the water content in paper, oxygen concentration and hotspot temperature as described in IV.C. Oxygen isn't measured in online data, so it was interpolated from offline data keeping the values until new measure is available. For periods where there are absence of online data it was assumed an initial value of water content in paper of 0,5% (usual value for new power transformers) and when there's no more data the last value was maintained and for hotspot temperature was assumed the mean of the estimated values.

Fig. 15 shows the evolution of degree of polymerization for the period of time where is possible to see the variation of it continuously in time, i.e., where online data is available.

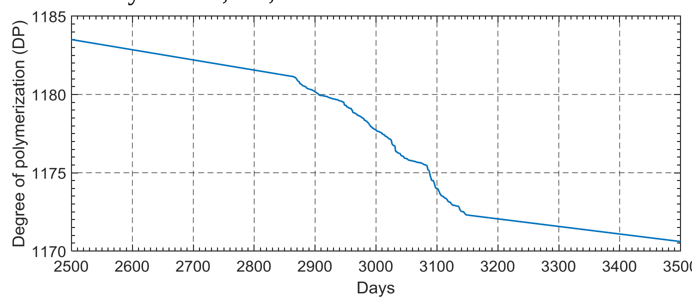

Fig. 15 – Degree of polymerization for days where is online data available

So it is possible to update the daily curve of degree of polymerization in order to have an approximate perception of solid insulation state continuously in time.

D. *Load model*

The load model is to determine whether the load exceeds or not the 200% limit, in this case the load factor must be between -2 and 2. As can be proven by the figure 16, where it's possible to see the evolution of load factor with a time step of 2 in 2 minutes, the load factor never exceeds the specified threshold, as such, should not "sound" no alarm.

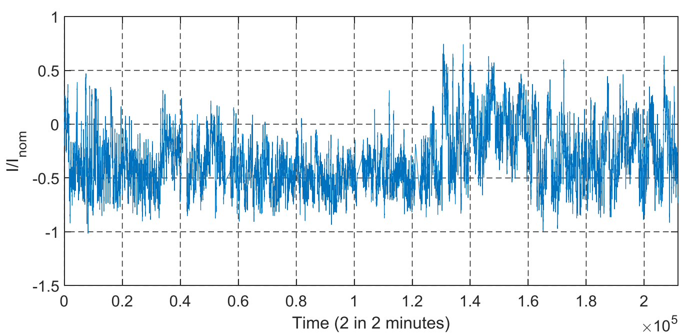

Fig. 16 – Evolution of load factor

E. *Dissolved gas-in-oil analysis model*

In order to be possible to apply the methods for dissolved gas-in-oil to online data it was estimated the concentration of CH_4, C_2H_6 and CO_2. Firstly it was observed by offline data that there is a strong correlation between some gases. As in the online data measured gases are H_2, C_2H_2, C_2H_4 and CO, it's only important to understand which not measured gases are more correlated with these. Then using multiple regressions is possible to estimate one gas by others gases. So, using offline gases, multiple regression models were obtained for CH_4, C_2H_6 and CO_2. For CH_4 the best multiple regression model found is expressed by CH_4=-10,05+0,878.C_2H_4+0,064.H_2, for C_2H_6 the best model is C_2H_6=1,57+0,188.C_2H_4+0,024.C_2H_2 and for CO_2 is CO_2=133,986+0,258.H_2+2,.688.CO. Multiple regression models were obtained using “lm” function of R program. In next figures are presented the evolutions of these gases in online (blue) and offline (orange). Fig.17 show the evolution of CH_4 where it’s possible to verify that values of both data are close. CH_4 trend is very similar to C_2H_4 trend, presenting the same 3 distinct zones. In Fig. 18 is represented the evolution of C_2H_6 where as CH_4 the values of both data are close and the trend is very similar to C_2H_4 trend. Fig. 19 exhibit CO_2 evolution, again online and offline values are close. CO_2 presents a constant increase like CO.

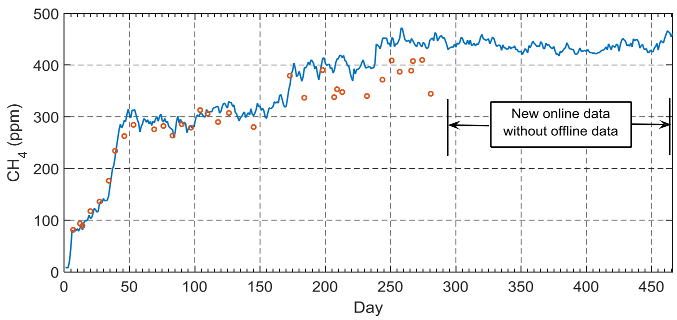

Fig. 17 – Evolution of ethylene in online (blue) and offline (orange)

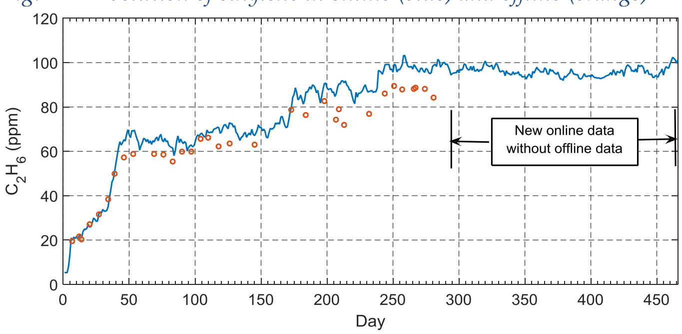

Fig. 18 – Evolution of ethane in online (blue) and offline (orange)

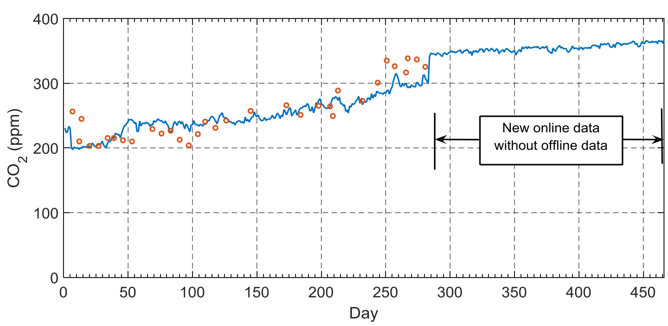

Fig. 19 – Evolution of carbon dioxide e in online (blue) and offline (orange)

To prove that online and offline data are close, errors for dates that have both data was computed, which figures in table 4. These errors comes from the deviations from the gases used for its estimations, as can be seen the relative errors are less or equal to 10% so this estimation is considered valid.

Table 4 – Errors between online estimated gases and offline gases calculated for days where there are both data

Gas	RMSE	AME	RME
CH_4	40,24 ppm	30,85 ppm	10,13%
C_2H_6	8,3 ppm	6,82 ppm	9,75%
CO_2	23,13 ppm	17,95 ppm	6,93%

It is then possible to apply methods for dissolved gas-in-oil analysis to online data. As for offline data the applied methods are Duval and IEC, the same will be applied to online data in order to compare the results. After analyzing the results of these methods for offline data it was concluded that the concentration of gases limits imposed corresponds to the ones of IEEE Std C57.104-91 presented on table 1. It was also verified that there aren’t imposed limits for rate of change, although trend of gases and its stabilization or not are highlighted on comments. Fig. 20 shows the evolution of faults using Duval method for offline data (yellow) and online considering rate of change limit (blue) and not (dark blue). Blue line follows dark blue line, excepting values that it comes to 0 indicating there’s no fault. As can be seen both online and offline data give often the same result, it was verified that adding rate of change (ROC) limit the diagnostic was much more realistic, since it indicates no fault when gases concentration stabilizes. The codification of faults by Duval method represented in fig. 20 is: 0-“No fault”, 1-“PD”, 2-“T1”, 3-“T2”, 4-“T3”, 5-“D+T”, 6-“D1” and 7-“D2”. IEC method results are not displayed but the interpretation is the same, it was verified that offline data and online (without consider ROC) data give the same diagnosis.

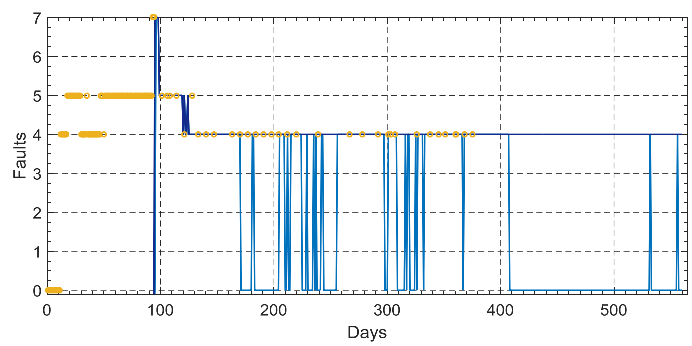

Fig. 20 – Evolution of faults using Duval method for offline data (yellow) and for online data considering rate of change (blue) and not (dark blue)

VII. Conclusion and Future Work

This report show how online monitoring and diagnostic models should be applied. It wasn’t possible to determine the component(s) that cause the faults detected in dissolved gas-in-oil analysis model because there aren´t data for all components and some data are doubtful, like water content oil values. However some techniques for implementation of this models in absence of some data are demonstrated and a model to monitoring and diagnostic online tank condition was developed.

In future it’s pretended to improve tank model. Some interesting ideas are determination of fault location using historical information, or online turns ratio implementation, or estimation of power transformer temperature by ambient temperature, load factor and wind using artificial intelligence techniques.

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