FIELD EXPERIENCE IN ON LINE MONITORING OF ONE 343MVA 230kV TRANSFORMER WITH 2 TAPS UNDER LOAD

Authors: Marcos E. G. Alves - TREETECH – marcos.alves@treetech.com.br
Gilson S. Silva – ALUMAR – gilson.s.silva@alcoa.com.br

Summary

In 2001, the first commercial on-line power transformer monitoring system top operate in Brazil was installed at Alumar, one of the world's largest aluminum production complexes. The system was installed on a 343MVA 230-34.5kV three-phase transformer with two taps under load, one on the high voltage and another at the medium voltage side. This article describes the system's architecture, based on a decentralized data capture philosophy and using intelligent electronic devices, for the associated monitoring and diagnosis features. The article also brings practical experience obtained during the implementation and operation of this system in the last 5 years, includinga detection at an early stage of a mechanical problem in one of the taps under load.

1. Introduction

ALUMAR is considered one of the world's largest alumina and aluminum industrial complexes, being formed by a consortium of the companies Alcoa, Bhpbilliton, Alcan and Abalco. The complex currently has an approximate annual output capacity of 1.5 million tons of alumina and 380 thousand tons of aluminum. The plant is basically divided into two areas, Reduction and Refinery.

Reduction received this name because of the electrolytic reduction process of alumina required in producing aluminum, which usually is carried out there. In order to perform the reduction, a material quantity of electric energy is necessary. Just this area of Alumar has an average monthly demand of 765MW and average monthly consumption of 570GWh. ALUMAR ie connected to the base grid receiving energy from Eletronorte at 230kV.

The process of reduction of aluminum requires a reliable energy supply without interruptions lasting longer than 2 hours. If this should happen, an entire production line will be frozen and losses will run to millions of US dollars.

With this, the company's electrical system, as well as its power transformers are an essential asset in this line of business, fact that led Alumar to purchasing a new 343MVA reserve bay that in 2001 joined the existing four. Each existing bay has a 230-34.5kV transformer on the power range of 300MVA with one On Load Tap Changer on the high voltage side and a voltage regulator transformer for 34.5kV, also equipped with one On Load Tap Changer. However, for the new bay, the option made was to build both transformers in the same tank, resulting in equipment with two commuters under load, one conventional, with oil-based arc extinction, on the 230kV side and one commuter with vacuum ampoule extinction, on the 34.5kV side.

While still in the acquisition process, the equipment specified preparation to receive future implementation of an online monitoring system. This system was purchased from, installed on the field and started up by Treetech still in 2001, immediately after delivery and commissioning of the transformer. This way, this monitoring system was the first to be installed and to start operating regularly in Brazil, being a pioneer for the fast growing broad acceptance of on-line transformer monitoring seen in these last years.

2. Architecture of the on line monitoring system

The online monitoring system installed (Sigma, by Treetech) uses a modular and decentralized architecture [1],[2], based on Intelligent Electronic Devices (IEDs) installed on the control panel on the transformer's casing, from where data is sent via serial communication to a computer at the plant's control room, which runs the software in charge of storing, making available and treating the information received, as shown generically by figure 1. These three main parts that define the monitoring system's architecture are described below.

2.1. Intelligent Electronic Devices (IEDs)

A few of these IEDs perform primary transformer control functions and therefore are used in the transformer regardless of the presence of a monitoring system. The equipment that already exists in the transformer is integrated into the monitoring system through one of its serial communication ports, in order to work simultaneously as sensors by supplying data for the system, without however adding any additional costs.

Other sensors were installed specifically for use by the monitoring system, but also within the philosophy of decentralized IEDs integrated to the system through their serial ports. In those few cases where it was impossible to integrate them to the system by way of serial communication, whether because the devices are not intelligent devices, or because the manufacturer does not offer open protocols at the serial ports (using only proprietary protocol), universal data acquisition modules were used, capable of receiving multiple digital and/or analog signals and digitizing them and making them available through open protocol serial ports.

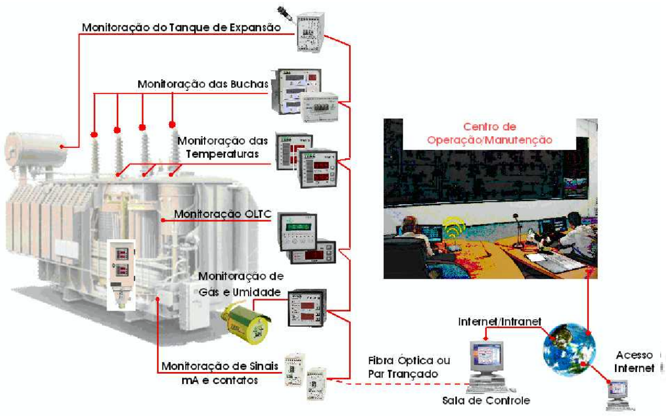

Figure 1 – Architecture of the monitoring system

In this way, it was possible to integrate every sensor, both intelligent and conventional ones, to the monitoring system through serial communication. This also avoided having to use any type of data centralizing equipment on the transformer casing, which simplified both design and installation, reduced initial costs and, the most important, also reduced TCO (Total Cost of Ownership) for the system in the same proportion that it increased reliability and availability.

Another characteristic obtained from decentralized architecture, by deploying IEDs, is the system's modularity, allowing free choice of variables for monitoring, in addition to facilitating future expansions simply by adding new IEDs. Several factors can be taken into account in making these choices, including the transformer's asset value, its importance in the productive chain (or in energy generation, transmission or distribution systems), among others.

2.2. Physical communication means

The physical medium used for communication in this case is a copper, shielded twisted pair cable. Even though optic fiber solutions were available and possible, at higher costs, there a conviction based on the features of the RS-485 communication standard, that this option could be used with satisfactory results. Among these characteristics is the fact that RS-485 operates in differential mode, which associated to the mutual cancellation of interferences in adjacent legs of the twisted pair makes this standard less susceptible to the interferences already expected in substations for this level of voltage.

As expected, the twisted-pair solution has shown to be totally satisfactory in spite of a complicating existing in this facility, which are the high intensity magnetic fields generated by the high currents employed in producing aluminum.

It is worth highlighting that, as alerted by Lavieri et. al. [3], essential in the success of this strategy is the fact that the IEDs used are equipment devices developed specifically for the substation environment where they are being used. Equipment originally developed for industrial purposes, when used in this type of application usually have fragility and lack of reliability related problems for the serial communication ports when subjected to electromagnetic surges and voltage impulses, in addition to the extreme external ambient temperatures.

2.3. Information storage, availability and Treatment

The data supplied by the IEDs located on the transformer, both raw readings and those supplied resulting from the pre-treatment of the data, are received by a computer running the monitoring software, in this application located in the plant control room.

The main functions of this software can be grouped in two classes, Data Digitizing functions, associated to simple data availability and storage, and Monitoring functions, with the objective of transforming simple data items into information useful for maintenance. In the monitoring system at Alumar, the following functions were created:

- Data Digitizing functions:
  - on-line presentation of readings, alarms and states
  - Storage of readings, alarms and states in history databases
  - Query readings, alarms and states stored in history databases in chart or table formats
  - Remote or local access to the system.
- Monitoring functions:
  - Algorhythm based data treatment
  - Mathematical model based data treatment
  - Transformer current status diagnostic
  - Transformer future state prognosis
  - Early stage defect detection.

3. Monitoring functions

In systems where the final objective is obtaining useful information for transformer maintenance, such as state diagnosis and prognosis, the Monitoring function block acquires special importance, which was confirmed in practice in this set up when a defect was detected in the On Load Tap Changer while still in its incipient stages (see item 4.1).

Similar to what occurs in the IEDs used in reading data acquisition, the system's data monitoring functions are also organized modularly, allowing free choice of the monitoring functions desired for installation, in addition to facilitating future expansions simply by the addition of new software modules and their corresponding IEDs. As already explained above, several factors can be taken into account in this choice, such as the value of the transformer or its importance in the electrical system, among others.

Following this modular philosophy, the monitoring system in operation at Alumar was equipped with the monitoring items described below, considered at that time as the most important for this application, even though any other items among those currently available can be added at any moment.

3.1. Insulation Life Cycle

This monitoring function performs the calculation of the estimated insulation life cycle loss due to the thermal aging of cellulose, in accordance with the load and temperature undergone by the transformer. It also calculates the average life cycle loss rate and extrapolation of the theoretical remaining life cycle for the insulation, as described in the next item.

3.1.1. Cellulose degradation mechanisms

The main component of the different solid insulating materials used in high voltage equipment immersed in liquid, among which stand out power transformers and reactors, bushings, PTs, CTs, etc., is cellulose. Among the solid insulation materials, the most commonly used currently is paper.

Cellulose is an organic compound, whose molecule is comprised by a long chain of glucose rings, or monomers. Each molecule of cellulose, when new, has between 1000 and 1400 glucose rings, interlinked as shown in figure 2. Each cellulose fiber has many monomer chains like this one.

The number of glucose rings interlinked in this chain is called the Level of Molecular Polymerization. Since it is the length of these molecules that afford the mechanical resistance of cellulose-based materials, the level of polymerization of the material gives us an indirect indication of the material's mechanical characteristics, such as for example the resistance to traction, which can be associated to the material's functionality or life cycle.

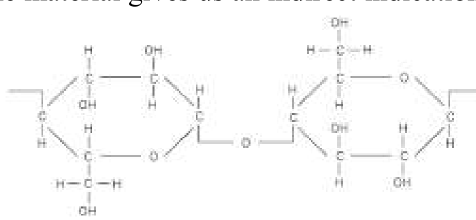

Figure 2 – Molecule of cellulose

The degradation of cellulose is, therefore, caused by reduction in the length of monomer chains, as well as by the condition of each chain. Three mechanisms may contribute towards the degradation of these chains in the cellulose employed in manufacturing power transformer insulation systems and for similar equipment: Hydrolysis, Oxidation and Pyrolysis [4]. Even though the latter one is related directly to thermal degradation, they all interfere in this aging process, so that all three mechanisms are inter-related.

3.1.1.1.Hydrolysis

Water caused breaks in the monomer chains by affecting the oxygen atom that bridges the rings. Two –OH groups are formed, each attached to a monomer. As a result there is a reduction in the level of polymerization and consequent weakening of the cellulose fiber.

Fabre & Pichon [5] formulated a simple rule for the degradation of cellulose as a function of the water content present. They proposed that the rate of thermal aging of cellulose is directly proportional to the water content. So, if the results of the thermal aging tests point to a given degradation rate for a given level of water content, equipment operating with double the water content will have a thermal degradation rate for the insulation twice as high as the one measured in the assay referred. Data obtained by Shroff e Stannet [6] confirm this relation, illustrated by the following equation:

$P_V \propto Q_P$, where:

P_V is the rate of loss of life for the insulation, and

Q_P is the water content of the insulation paper.

3.1.1.2.Oxidation

The carbon atoms of the cellulose molecule are attacked by the oxygen, forming aldehydes and acids. Consequently, the union between the rings is weakened, leading to low levels of polymerization. Water, carbon monoxide and carbon dioxide are released. The water released by this process will also contribute to the hydrolysis process described above.

Not only is the cellulose attacked directly by the oxygen, but also the oil undergoes oxidation, producing acids, esthers and other substances that, in their turn, also attack the oil, generating even more oxidation products. These substances also attack cellulose, further degrading it.

The effect of the oxygen on the degradation rate of cellulose has been investigated by several researchers, and the most common procedure is comparing the results of aging rates from samples taken in sealed insulation, free from oxygen, with rates of samples exposed to the atmosphere, like in transformers without oil preservation systems. Some of the researchers into this phenomenon were Fabre [5] and Lampe [7], who found degradation acceleration factors for the samples exposed to oxygen in relation to those in sealed samples of 10 and 2.5 times, respectively.

It is clear that the presence of oxygen has an extremely adverse effect on the aging of cellulose, and must definitely be avoided. If the oil preservation system fails, allowing the oil to come in contact with the atmosphere, we can expect the aging process to be considerably accelerated.

In order to avoid this risk, the monitoring system includes a sensor to monitor the rubber membrane that prevents contact between the oil and the atmosphere. If this membrane ruptures, an alarm is issued by the monitoring system.

3.1.1.3.Pyrolysis

Extreme heat leads to carbonization of the cellulose fibers. On the other hand, moderate intensity heat, as is usually found on transformers, causes rupture of the individual monomers of the cellulose chain, forming a solid waste product releasing carbon monoxide, carbon dioxide and water. Again, the level of polymerization is reduced, weakening the mechanical resistance features of the cellulose.

Since in transformers, temperature is not distributed uniformly, in general analysis heat effects in the deterioration of cellulose is performed considering the temperature of the hottest spot, since this will be the site where the highest level of degradation will occur.

3.1.2.On-line Monitoring of Insulation Aging

In complying with the Brazilian loading standards for power transformer loading, the expected life cycle duration for transformer insulation with insulating oil characteristics for new oil (neutralization index, oxygen dissolved in oil content and water content in controlled insulation) is given exclusively by Arrhenius's Law, where the logarithm of the life expectation is a function inverse to absolute temperature:

log (life) = A + B / T , where:

A and B are constants, and

T is the temperature of the hottest spot.

The chart in figure 3 visualizes Arrhenius's law in the format of annual life consumption for the insulation for different values of temperature of the hottest spot, supposing the temperature remaining constant throughout the period.

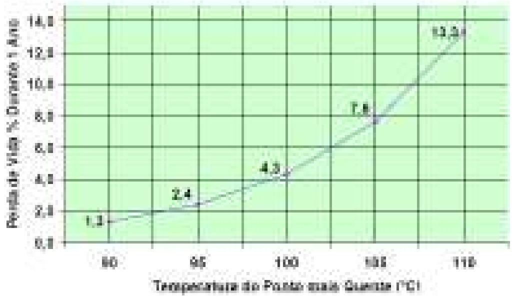

Figure 3 – Annual loss of life for insulation subjected to constant temperature

Since, in practice, the temperature of the hottest spot varies according to changes in load and ambient temperature, loss of insulation life is calculated in short time intervals during which the temperature remains practically constant. The small losses of life incurred in these time intervals are accumulated for the entire system operation time, giving total loss of insulation life cycle.

$P_{total} = \Sigma P_i$, where:

P_{total} is the total aggregate loss of insulation life cycle,

P_i are losses in insulation life for the small incremental time intervals, and

As described above, in item 3.1.1.1, the water content in the insulation also plays a major role in the insulation's loss of life rate, by accelerating the degradation of the insulation proportionally to the existing water content. This way, the thermal life loss can be calculated by the monitoring system is corrected for the water content found in the insulation, which can be calculated by the system or an estimated fixed value can be adopted.

Based on the aggregate percentage loss of insulation life data, it is possible to extrapolate the remaining expected life time, by observing the evolution of the rate for loss of life for a period in the past that is representative of the average operating conditions for the equipment.

3.2. Forecast of Final Temperature Gradient

This monitoring function calculates future values of the oil/winding temperature gradient and issues an alarm when a trend that will lead the winding temperature to reach temperature alarm levels or shut down is detected, in addition to informing the time remaining before alarm and/or shut down temperatures are reached.

3.2.1.Rising winding-oil temperature

Applying loads to power transformers causes the temperature of the hottest spot on the winding to rise in relation to the temperature at the top of the oil which is a function of the load applied and the system's specific loss and heat exchange features. This principle is also used in determining the temperature of the winding by the process called "thermal image":

$\Delta\theta_{EO} = f\,(l,c)$, where:

$\Delta\theta_{EO}$ is the rise in winding temperature over the top of the oil,

l is the load, and

c are the transformer's own characteristics.

Figure 4 – Rise in winding-oil temperature as a function of the load

For each load value applied there is a corresponding value in rise of the temperature of the winding over the top of the oil, as in the example shown in figure 4.

In this example, we can observe that the rated load (100%) corresponds to a rise in rated temperature of 30ºC, value obtained in transformer heating tests. However, due to the thermal inertia of the mass of copper/insulating material, applying a given load does not immediately bring about an instant rise in the temperature corresponding to the shown above. This inertia causes the temperature of the winding to rise gradually from the current value to the new value (corresponding to the new load) following an exponential curve for a given time constant.

3.2.2.Monitoring of Final Gradient of Winding-Oil Temperature

As shown in the chart in figure 4, when a given load is applied on a transformer, it is possible to know what the winding's final temperature will be after thermal stabilization is achieved.

This allows forecasting, in short term horizons, whether the rise on the winding over oil temperature will lead to achieving levels that will trigger off the equipment's protection systems to issue alarm signals or even shut down conditions.

If the temperature forecast for the system exceeds this value adjusted for alarming, the monitoring system issues the alarm for this condition, also informing the time remaining before the calculated alarm, value is reached based on the winding's thermal time constant.

Figure 5 shows an example of the evolution expected for the temperature of the winding, the time to reach the alarm value and the final winding temperature value after stabilizing. In this example, when an overload is applied to the transformer, the monitoring system would initially calculate the time remaining of 13 minutes before the alarm (or shut down) temperature is reached, with calculation being continually readjusted.

Likewise, the same process of extrapolation for future temperature rises of winding over top oil can also be applied to the temperature rise oil over ambient, allowing trend monitoring for future rises in temperature with advance warning on the order of hours.

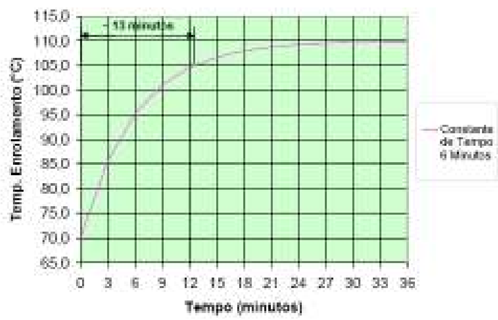

Figure 5 – Evolution of winding temperature in time

3.3. Gases in Oil

This monitoring function performs on-line supervision of the concentration of hydrogen dissolved in oil. Since hydrogen is a gas generated in nearly every type of internal defects that can occur in transformers, it is considered a key gas in defect detection.

In this way, based on the ongoing follow up of the hydrogen in oil content, the monitoring system can issue alarms in case high levels hydrogen content are reached such as, for instance, detection of rising trend for the content of this gas that will in future reach these high levels.

3.4. Moisture in Oil

As already explained in item 3.1.1.1, the presence of moisture in the insulating paper potentializes the effects of the thermal degradation of the insulation in proportion to the content of water present.

This way, maintaining reduced water content in insulation levels is essential. During the manufacture process, the active part of the transformer undergoes strict drying processes, with the same occurring with the oil employed in the equipment's first tank full. This way, the new equipment has assurance of low water content in the insulation paper.

From this point on, several different processes can lead to increased water in insulation content. Included among these is the degradation of cellulose, which generates water, however the main rise factor can be entrance of water from the environment through flawed seals. In this case, the water found in the environment is absorbed first by the oil, from where it migrates to the insulation paper.

This way, the monitoring system first checks the integrity of the seals of the oil expansion tank, by supervising for rupture of the rubber membrane that prevents the contact of the oil with the open environment, and in addition to this, also monitors the water dissolved in oil content.

This monitoring function performs on-line supervision of the level of water dissolved in oil, issuing alarms for both, high content levels reached and rise trend detected that in future will result in high levels of water in oil.

3.5. Forced Ventilation Maintenance Assistant

Adequate cooling of transformers is essential in their safe operation without accelerated life cycle losses for the insulation when operating under heavy load regimes. In this transformers case, this is achieved by using several fans to force circulation of air through radiator sets (cooling type ONAF). Therefore, it is essential that these fans operate perfectly. Failure of one or more fans can cause activation of the protections for temperature or limit transformer loading, rendering the equipment only partially available.

For this reason, normal fan wear must be monitored, which is traditionally done off-line through the preventive maintenance scheme recommended by manufacturers. These interventions are usually based on equipment operating time, and include changes of components (for example, windings).

The Forced Ventilation Maintenance Assistant allows fan operation time to be known accurately, thus avoiding these manufacturer-oriented maintenance interventions to happen much before or after the time recommended by manufacturers. This monitoring function also offers several other items of useful information in order to help with fan maintenance:

- Total fan and pump operating time, from the beginning of operation, and time since last maintenance interventions, with records of motor start and stops;
- Average daily operating time for fans and pumps;
- Time forecasts until the recommended inspection or maintenance intervals are reached, based on daily average fan and pump operating time;
- Warnings issued with programmable advance for inspection or maintenance of the equipment because of operating time.

3.6. On Load Tap Changer Maintenance Assistant

All failure statistics for power transformers point to the On Load Tap Changer as one of the main sources of defect, in particular due to the moving parts that conduce and interrupt high currents while subjected to high voltages.

For this reason, this monitoring function helps in supervising regular commuter wear, which is traditionally done off-line through the preventive maintenance scheme recommended by manufacturers. These interventions are usually based on the number of tap changes and equipment operating time, and include visual inspections and contact thickness measurement procedures.

This monitoring function supplies several useful items of information to help with commuter under load maintenance:

- Sum total current commuted since beginning of service, to afford a rate of contact wear
- Total number of operations since the beginning of operation after last maintenance
- Calculation of total thickness of arc interruption contacts, by extrapolation based on previous thickness measurements and number of tap operations
- Total commuter service time and total service time since last maintenance
- Daily average contact wear and daily average tap changes
- Time to reach minimum contact thickness forecast or to reach number of operations or to reach maximum inspection or maintenance interval
- Warnings, with programmable advance, for commuter inspection or maintenance.

3.7. Commuter Operating Times

Commuters under load represent one fo the main sources of power transformer failures. The reason for this, as described previously, is the fact that commuters are mechanical equipment, based on moving parts. Thus, failures with mechanical origin in the On Load Tap Changer can cause problems with varied magnitudes, starting from equipment unavailability and going all the way to severe dielectric failures.

In this context, the function that monitors commuter operating times supervises the time required to perform the tap change in each operation of the commuter, issuing alarm in case this time deviates from the times observed during regular behavior operation of the equipment. In item 4.1, there is a description of how this function detected an actual flaw in one of the commuters under load.

4. Experiences in system installation and operation

4.1. Diagnostic of defect in one On Load Tap Changer

With early detection of failures being one of the main purposes of an online monitoring system, the most interesting event during the operation of the Alumar system was observed while still in the commissioning phase, when the system diagnosed a problem on the On Load Tap Changer on the 230kV side.

This diagnostic was issued from diagnosis function of the “Commuter Maintenance Assistant”, which among other parameters monitors time spent in carrying out each commutation. Through this measurement, a deviation was observed in relation to the history data stored in the system,.

When the On Load Tap Changer activation panel was inspected, oxidation was found on the cam tree of the activation mechanism that drove the activation motor to remain in operation longer than required to perform the commutation.

Once this was detected early, the defect was quickly corrected and did not actually cause a disturbance in the regular operation f the transformer. If, however, the transformer and the On Load Tap Changer were not equipped with an online monitoring system, the trend would be for the problem to slowly become more serious unnoticed. After a certain point, the On Load Tap Changer wiuld “shoot” up or down, rising or lowering voltage, when the maximum or minimum tap positions were reached. This way, depending on the voltage level present at the 230kV input, voltage regulation for the process of manufacturing aluminum could be severely impaired, with including the risk of loosing production.

4.2. Serial communication in metal pair

Because it was the first commercial system to operate in monitoring on-line for transformers in Brazil, in 2001, one of the points to be checked when it started to operate, was to prove the feasibility of using serial communication RS-485 with copper cables in substations. This objective was fulfilled when they operated satisfactorily even in very adverse electromagnetic interference conditions found in the facilities, which has been attested by these nearly six years of operation of the system.

4.3. Compatibility with other existing systems

Still during system installation, for space limitation issues, Alumar wished to avoid installing an additional PC in the control room, which would have happened if the option made was for a dedicated computer to run the monitoring system. It was believed that the monitoring system could be installed in the same computer already running the supervisory system, which was confirmed during installation and long term operation of the system, without any compatibility problems between the systems.

5. Conclusions

Because at the time, this was the first system to operate commercially among commercial on-line transformer monitoring systems, many expectations surrounded the system object of this article. In fact, shortly after it went into operation, facts evidenced the gains achieved with the installation of the system, when the system detected a defect in one On Load Tap Changer that, under other conditions, would slip by unnoticed and might cause severe future losses.

This fact shows that the savings that can be obtained from using an online monitoring system in avoiding more severe failures, showing that the cost barrier, often singled out as impediment to installing monitoring systems, can be an illusion.

To the above exposed, we should add the fact that monitoring systems based on decentralized architectures can be assembled modularly in accordance with each application's needs and budget, allowing for the system's future and gradual expansion.

6. Bibliography

[1] Alves, Marcos, "Online monitoring system de Transformadores de Potência", Revista Eletricidade Moderna, Maio/2004.

[2] Amom, Jorge, Alves, Marcos, Vita, André, Kastrup Filho, Oscar, Ribeiro, Adolfo, et. al., "Sistema de Diagnósticos para o Monitoramento de Subestações de Alta Tensão e o Gerenciamento das Atividades de Manutenção: Integração e Aplicações", X ERLAC - Encontro Regional Latinoamericano do CIGRÉ, Puerto Iguazu, Argentina, 2003.

[3] Lavieri Jr., Arthur, Hering, Ricardo, "Novos Conceitos em Sistemas de Energia de Alta Confiabilidade", Encarte Especial Siemens Energia, http://mediaibox.siemens.com.br/upfiles/232.pdf, Janeiro/2001.

[4] McNutt, W. J., "Insulation Thermal Life Considerations for Transformer Loading Guides", IEEE Transaction on Power Delivery, vol. 7, No. 1, pp. 392-401, January 1992.

[5] Fabre, J., Pichon, A., "Deteriorating Processes and Products of Paper in Oil. Application to Transformers", CIGRE Paper 137, 1960.

[6] Shroff, D. H., Stannet, A. W., "A Review of Paper Aging in Power Transformers", IEE Proceedings, vol. 132, Pt. C, No. 6, pp. 312-319, November 1985.

[7] Lampe, W., Spicar, E., Carrander, K., "Continuous Purification and Supervision of Transformer Insulation System in Service", IEEE Winter Point Meeting, IEEE Paper A 78 111-7, January/February 1978.