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ON-LINE MONITORING AND DIAGNOSIS OF POWER TRANSFORMER WITH VEGETABLE OIL

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ABSTRACT

The replacement from mineral insulating oil to fluid of vegetable origin in power transformers has aroused a high level of interest in the last years. This is due the several factors such as increased flash point, the high water solubility, which can allow the insulating paper keep itself drier, and the non-toxicity and biodegradability, which become it environmentally attractive, amongst other characteristics.
For this reason, Cemig Distribuição has included the transformer usage with vegetable oil as one of its strategic initiatives for improving its technical and economical performance indicators.
Once such equipment perform essential roles in power electric system, eventual failures can cause large prejudices, not only due the damages in the equipment, but also due loss of revenue, contractual penalties, and reliability decrease of the power system. In this context, the equipment on-line monitoring has an essential role for diagnosing its condition, and in several cases it can detect failures still in incipient phase, in addition to indicate potential causes. Hence, larger damages to the equipment or even its total loss may be prevented.
This paper will present the experiences with this equipment on-line monitoring, including some specific aspects related to the type of used insulating fluid.

KEYWORDS

On-line Monitoring, Vegetable Oil, Decentralized Architecture, Specialized Systems

1.1 - INTRODUCTION

Vegetable oils are organic components based on ester, natural agricultural products, or those chemically synthesized by organic precursor. dielectric fluids based on synthetic ester, also known as POE, have good dielectric characteristics [1] and are more biodegradable than the mineral oils based on high molecular weight hydrocarbon (HMWH). Moreover, they have excellent thermal stability, good properties in high temperatures, pour point next to that conventional mineral oil and dielectric strength and viscosities similar to the formulation with natural ester. However, they present lower ignition point and slower biodegradation rate than the natural ester. Their high cost comparing with other fire-resistant fluids [2], generally limits their usage in movable substations, traction transformers, and other special applications.
Natural esters are seed-base oils, including the glycerol-derivative fatty fluid known as triglycerides. They were deem inappropriate for using in transformers due to their high susceptibility to the oxidation. Given the growing demand for viable options to the mineral oil, the researches increased and several oil mixture were evaluated. By finding the best way to balance them, oxidation and fluidity characteristics enhancement started. Thus, addictive selection started in order to improve the fluid performance.

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The natural ester has viscosity slightly higher than the mineral oil, greater resistance to the fire, and higher dielectric strength, both in the new fluid and after multiple switching operations under load. The negative aspect is its relatively high pour point.
An attractive source of natural esters is the seed oils. These seeds, which are derivative from renewable natural sources, different to the mineral oils, available in large scale and with reduced production cost are used mainly in foodstuffs. The vegetable oil formulation does not present any toxicity to be human being and has degradation time lower than the mineral oils. Moreover, the products of its entire ignition are only carbon dioxide and water. The fluid can be filtered, recycled, and easily disposable.

1.2 Vegetable and mineral oil thermal characteristics

In despite of its highest viscosity, natural ester thermal performance ban be compared with the conventional mineral oil. In the worst case, the average increase of the winding temperature of the transformers isolated to vegetable oil is about of 5ºC higher [1] than mineral oil. However, in figure 01, the high flash and ignition point of the vegetable oil is verified. Thus, it is possible to allow the operation temperature increase of the insulating oil without affecting the transformer safety.

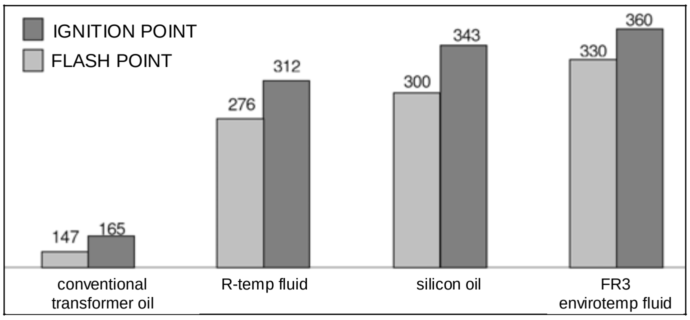

Figure 01 – Comparison of typical flash and ignition points of insulating fluids

1.3 INSULATING PAPER AGING IN VEGETABLE OIL

One pertinent concern to the adoption of the vegetable oil in transformers is the insulating paper durability, i.e., the way the new insulating affects the solid insulation shelf life. Published studies [1-3] demonstrate that, under the same conditions, kraft paper aging in vegetable oil is very slower than in conventional mineral oil. The main kraft paper degradation factors in transformers are: temperature (thermokinetic degradation) and water amount (thermo-hydrolytic degradation).
In terms of related saturation, a balance point must be obtained between the paper and the insulating oil in usual operation. Natural esters can accommodate a higher water amount than the mineral oils, causing more water is displaced from the paper to the fluid. This is one of the a favorable characteristics of the natural esters used as insulating, since there is a significant increase of the paper shelf life.
Figure 02 shows a comparison test of the aging rate of the paper thermostabilized with mineral oil and natural ester, and this latter is significantly slower. It is estimated the thermostabilized paper in a natural ester transformer with average increase of temperature of 85ºC has the same shelf life than a similar paper in a mineral oil transformer with average increase of temperature of 65ºC. In other words, for the same shelf life, the thermostabilized paper impregnated with vegetable oil can operate at a temperature 20°C higher than the paper with mineral oil. The importance of this result is large in the project of new transformers or in the repowering of used transformers, since the prorogation effect of the insulation shelf life immediately represents lower project costs or increase of equipment shelf life.

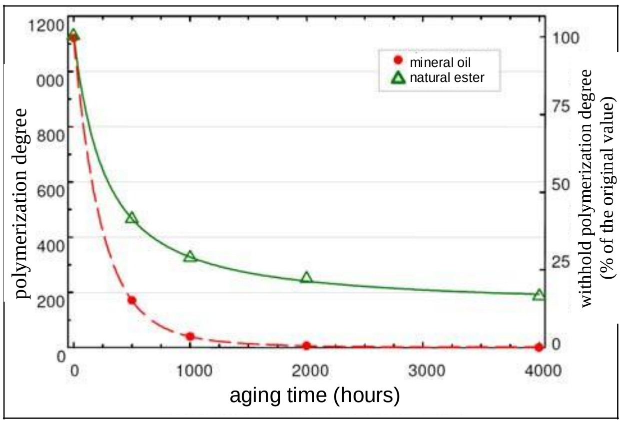

Figure 02: Comparison of the insulating paper aging with different insulating fluids.

2.0 - ON-LINE MONITORING OF THE TRANSFORMER FILLED WITH INSULATING VEGETABLE OIL

As the vegetable oil technology is still in experimental phase and tests against several electric, thermomechanical, and chemical stresses, the on-line monitoring was deemed essential for the evaluation of its performance in power transformers.
The on-line monitoring system also collects and stores all the monitored information, allowing the development of subsequent studies, encompassing the analysis in a wide variety of situations. Tusa, was the transformer chosen for the installation of the monitoring system, which was rebuilt in 2007 by ABB, and filled with insulating vegetable oil in the main tank and also in the switch. In table 01, some data related to such transformer are presented.

Table 01: Monitored transformer data

Type:	Three-Phase Regulating Transformer
Voltage:	138 kV – 13.8 kV
Power:	25 MVA
Manufacturer:	Tusa (Rebuilt by ABB in 2007)
Voltage class:	138 kV
Year of manufacturing:	1977 (2007)
Oil volume:	15,500 liter
Type of Oil:	Insulating vegetable oil Biotemp, from ABB

3.1 - ARCHITECTURE OF THE ON-LINE MONITORING SYSTEM

After verifying all needs and consulting the literature [4-8], a specification was prepared contemplating and taking into account the state of art in on-line monitoring systems, directing the devices and used architecture choice.

3.2 <u>on-line ACQUISITION of measurement</u>

In order to measure the variables in the transformer, a decentralized architecture was chosen, as shown in figure 03, wherein specialized modules for each intended measurement are observed. Such architecture presents several interesting characteristics, which are showed in table 02.

Table 02: Main characteristics of the used Decentralized Architecture

The sensors are IED’s (Intelligent Electronic Devices), which send the information directly to the data management block of the monitoring system
Modular system, making ease future expansions and maintenance
IED’s already existing in the control and protection systems can be integrated to the monitoring and data acquisition systems, preventing costs of additional sensors
There is no centralizing element – additional costs are avoided
There is no centralizing element – potential additional points of failure are avoided
Failure in an IED causes loss only in part of the functions – other IED's reaming in service
Operation temperature -40 to +85ºC, proper for installation in the patio, together with the transformer
Installation together with the transformer, in the patio – only serial communication (twisted pair, optical fiber or mobile phone modem GPRS) for interconnecting with the data management block of the monitoring system
Typical insulation level 2,5kV – designed for the environment of high-voltage substations.

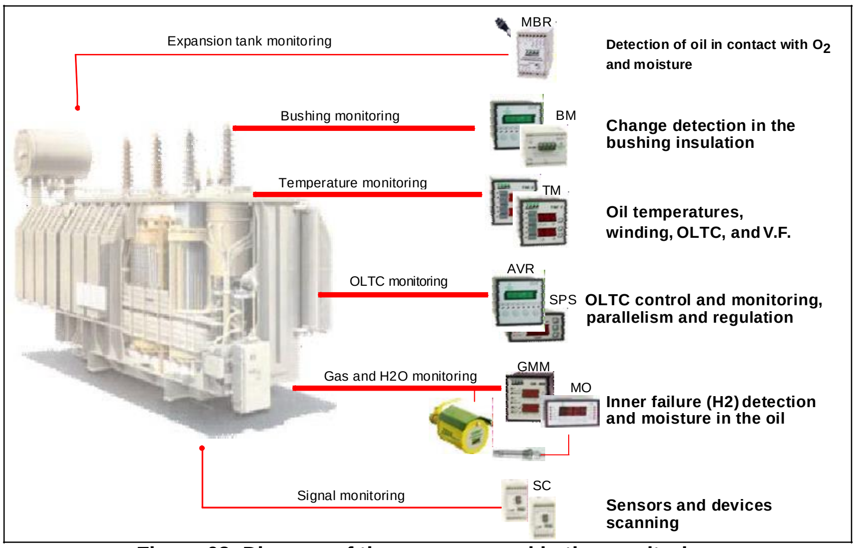

Figure 03: Diagram of the sensors used in the monitoring.

Table 03 details the measurements carried out by each one of the IED sensors installed in the transformer.

Table 03: Measurements carried out by IED sensors

IED's	Acquired data
Temperature Monitor	- Oil temperature - Hot-spots temperatures of the windings - Load currents - Alarms and disconnections due high temperatures
Gas monitor in the oil	- Hydrogen dissolved in the transformer oil - Alarms due high/very high gas - Oil temperature in the measurement point
Transformer moisture monitor	- Related water saturation (%) in the transformer oil - Water content in the transformer oil (ppm) - Room temperature - Oil temperature in the measurement point
Switch moisture monitor	- Related water saturation (%) in the switch under load oil - Water content in the switch under load oil (ppm) - Oil temperature in the measurement point
Membrane relay	- Rupture of the conserver tank's bag
Voltage and Current Transducer	- Switch engine voltages - Switch engine currents - switch engine active/reactive/apparent powers
Data acquisition module	- Alarm contacts (buchholz relay, relief valve, oil level etc.) - Condition of the forced ventilation groups - Switch under load in operation - Operation time of the switch under load
Bushing monitor	- Bushing capacitances - Bushing tan delta
Voltage regulating relay	- Phase Voltages - Phase Currents - Active/reactive/apparent Powers

4.0 - ON-LINE REMOTE TRANSMISSION OF MEASUREMENTS

Once the sensors are installed in the transformer, it is required the measurements are transferred to a data management system, in which the calculation and algorithm are carried out in order to obtain useful information, such as the condition diagnoses and prognoses of the transformer. The architecture used for such function is showed figure 04.

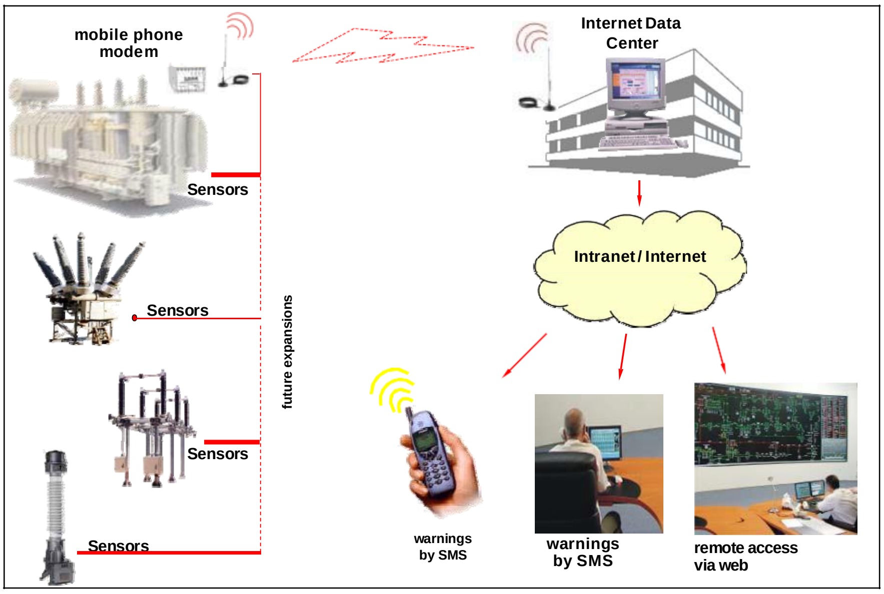

Figure 04: Architecture for measurement transmission, data management, and remote access to the on-line monitoring system.

As per observed in figure 04, the sensors in the power transformer are interconnected each other and with mobile phone modem GPRS in a serial communication network. Future monitoring system expansions, for including new sensors in the transformer or new equipment of the substation (circuit-breakers, TC's, TP's, lightining arresters etc.) can be easily performed, adding only the new sensors in the communication network.
Then, the modem transmits the sensor measurements for the monitoring software using the mobile telephony network, through the GPRS (General Package Radio Services) data transmission protocol, which is the same used, for example, for transactions with credit card using wireless terminals. The information is received in a computer located in an IDC (Internet Data Center), described below.

5.0- DATA MANAGEMENT FOR DIAGNOSIS AND PROGNOSIS

The data provided by the sensors IED's located in the transformer is received by a computer, in which the monitoring software is executed. In this application it was chosen to execute the software in a computer located in an Internet Data Center (IDC) contracted and managed by the application provider.
IDC is an independent company, specialized in store and data processing service, which has all required infrastructure for the reliability and availability of the monitoring system, including:

- Servers with high availability (24h x7 days/week);
- Contingence for electric power shortage, with no-breaks and emergency generating groups;
- Broadband, assuring the access availability to the system;
- Daily automatic Backups;
- Firewall;
- Protocol https (safe website), through SSL (Secure Sockets Layer);
- Physical security with strict access control.

Please find below the main gains obtained with such solution, in which monitoring software is hosted in an IDC rather in Cemig's premises taking into account the monitoring system is a tool for the maintenance engineering:

- Assurance of monitoring software updating, since its execution in the IDC is directly managed by its manufacturer;
- Assurance of the hardware (servers etc.) updating, in the extent of the monitoring software growing, for example, with other transformers inclusion;
- Assurance of data integrity, due to backups automatically performed;
- Assurance of software continuous execution, without risk to stop due to power supply. Possibility (optional) of redundant servers;
- Assurance of access to monitoring information since any location, whether in the Cemig's regional, which approach a great geographic area, or out of the company – for example, during travels or off-hours, in any part of the world;

- Overload of the company’s inner IT staff with regular system maintenance is avoided, which would include the backups performance, no-breaks operation inspection, software updates (operating system, antivirus, monitoring software etc.), firewalls management etc.;
- Increased costs with acquisition, maintenance, and periodic update of hardware and software license are avoided.

6.0- FUNCTIONS OF SIGMA4WEB - DATA MANAGEMENT SOFTWARE

This software’s main functions can be pooled in two categories: Data Scanning and Monitoring.
Data Scanning:

- On-line acquisition of sensor data;
- On-line presentation of measurements, alarms, and status;
- Measurements, alarms, and status storage in historical database;
- Survey of measurements, alarms, and status stored in historical database as plots or tables;
- Automatic sending of warnings or alarms by e-mail or SMS.

Monitoring:

- Data management through algorithms;
- Data management through mathematic templates;
- Diagnosis obtainment of the current transformer condition;
- Prognosis obtainment of the future transformer condition;
- Detection of defects in incipient phase.

As per observed above, Monitoring functions aim to change the sensor measurements in useful information for the maintenance, which are the equipment condition diagnoses and prognoses. For that, Sigma4web has the named “Engineering Modules”, in which are the algorithms and mathematic templates for diagnoses and prognoses.
As with the IED's used for measurement acquisition, the monitoring functions (Engineering Module) of the system are organized in a modular manner, allowing the functions intended to be installed be freely chosen, in addition to facilitate future expansions joining new software modules and its corresponding IED's. The Engineering Modules used in the application are described in table 04 below.

Table 04: Management data modules for Monitoring, Diagnosis and Prognosis

Engineering modules	Monitored functions
Sigma Ageing	• Loss of insulation shelf life • Loss of shelf life rate • Extrapolation of the remaining life time, in years
Sigma Forecast	• Forecast of Future temperatures • Forecast of alarms or disconnections occurrence • Calculation of the remaining time for alarms and disconnections.
Sigma Efficiency	• Efficiency of the natural and forced cooling systems • Alarms in case of low cooling efficiency
Sigma Fan	• Hours of forced cooling group operation since the beginning of the operation • Hours of forced cooling group operation since last maintenance • Average of daily operation hours of the cooling • Extrapolation of remaining time for inspection or maintenance • Notices in advance for inspection or maintenance.
Sigma Hydro	• Water content in the Oil and in the Paper • Acceleration of loss of insulation shelf life due water excess • Bubble Generation Temperature • Free water generation temperature • Alarms due risk of bubble generation or free water
Sigma Chroma	• On-line measurement of hydrogen dissolved in the oil • Alarms due high, very high H2 content or increase trend

	• Database of off-line gas chromatography analyses • Calculation of the gas increase rates • Automatic opinions for the off-line gas chromatography analyses
Sigma Torque	• Torque of the switch under load engine
Sigma Simulation	• Loading simulation based on the current load and temperature conditions • Loading simulation with load and room temperature curves of the user
Sigma Specialist	Analysis of the warnings and alarms emitted by the monitoring system for indicating: • Probable causes (diagnosis) • Recommended actions • Future consequences (prognosis)

7.0 - EXPERIENCE WITH ON-LINE MONITORING SYSTEM

The assembly of the gas and moisture monitoring system was carried out during the transformer installation in the SE Pará de Minas 1, in December/2007 and January/2008. In figure 05 some figures of the device installation are showed.

Figure 05 - Sensor Installation in the transformer

Right after the transformer service delivery, the system performance evaluation started. It was verified the need of survey of actual solubility of the used oil, so that the sensors presented values suitable with the vegetable oil. Through the measurements stored in the monitoring system and physical-chemical and chromatographic oil analysis database it is possible to survey accurately such constants and then calibrate the sensors. Table 05 shows the values sampled by the monitoring system after the calibration with the correct constants. Such values were compared with the physical-chemical and chromatographic analyses carried out by the Cemig's lab and presented excellent results, with errors lower than 2% of the reference value, showing system efficacy and precision.

Table 05: Values presented during the H_2 and H_2O monitoring

	T_0 °C	$RS_{\%}$	H_2O PPM	H_2 PPM
Tank	33.4	1.8	20	N/A
	42.9	2.0	27	18
Switch	29.0	7.5	86	N/A

8.0 - CONCLUSIONS

The usage of the vegetable oil as insulating and cooling medium in high-voltage power transformers is recent if compared with the mineral oil. Thus, the permanent follow-up of its performance is required in order to prevent potential failures and know its behavior throughout the time in real work situations.
The usage of an on-line monitoring system with high performance and low cost supports this need. This system must be carefully specified so that really obtaining the intended performance, such fact is very important, due to the insulating fluid to be monitored is the vegetable oil.
The experience with this transformer monitoring with vegetable oil has demonstrated to be very promising, achieving the expected results and mainly, providing the tools for the best understanding of the vegetable oil and its particularities.

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