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Field Experience with On-Line Monitoring of Two 150MVA 230kV Transformers with On-Load Tap Changers

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Summary - In 2001 Eletrosul started operation of Itajai substation with two 150MVA 230-138kV power transformers with OLTC. This paper will present the philosophy and field experience with the On-line Monitoring of these transformers using a system with modular, decentralized architecture, based on Intelligent Electronic Devices (IEDs) installed on the transformer to transmit the measurements to a computer in the control room by a single twisted-pair cable. Processing of the measurements with algorithms and mathematical models transform them into useful maintenance information such as diagnostics and prognostics on the condition of the transformer. The system description and the six year field experience with the use of this tool will permit an evaluation of the benefits and experience gained with the monitoring system presented, allowing conclusions about the applicability of monitoring systems both in large and small power transformers.

Keywords: transformer, on-line monitoring, diagnostics, prognostics, predictive maintenance, condition based maintenance.

1. INTRODUCTION

Itajaí substation was built by Eletrosul Centrais Eletricas in 2001 to add 300MVA to its installed power and serve the demand of the East Region of Santa Catarina State. It reaches a contingent of 1.1 million people and gives better quality and reliability to the Interconnected System of the South Region of Brazil.

The substation initially received two three-phase power transformers 150MVA 230-138-13.8kV with On Load Tap Changers. Included in its strategy for migration from Preventive to Predictive maintenance Eletrosul specified these transformers for delivery already equipped with On-line Monitoring Systems, so as to guarantee reliability for the supply of electric power and reduce the outages for tests and maintenance.

At that time it was already in operation in the aluminum production plant Alumar (Alcoa group) the first power transformer on-line monitoring system to start regular operation in Brazil [1]. The same monitoring system (Sigma, Treetech) was thus selected to equip the two new power transformers. Sigma started operation in Itajaí substation in December 2001.

This way, this monitoring system was among the first ones to be installed and start commercial operation in Brazil. This paper will present the experience with the installation and operation of this system, which led Eletrosul to adopt the specification of on-line monitoring for the new power transformers bought since then.

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2. ARCHITECTURE OF THE ON-LINE MONITORING SYSTEM

The on-line monitoring system installed uses a modular and decentralized architecture [1], [2], [3] based on Intelligent Electronic Devices (IEDs) installed on the control panel on the transformer's tank, from where data is sent via serial communication to a monitoring server computer at the substation's control room. This computer runs the software in charge of storing, making available and processing the information received, as shown generically by figure 1. These three main parts that define the monitoring system's architecture are described below.

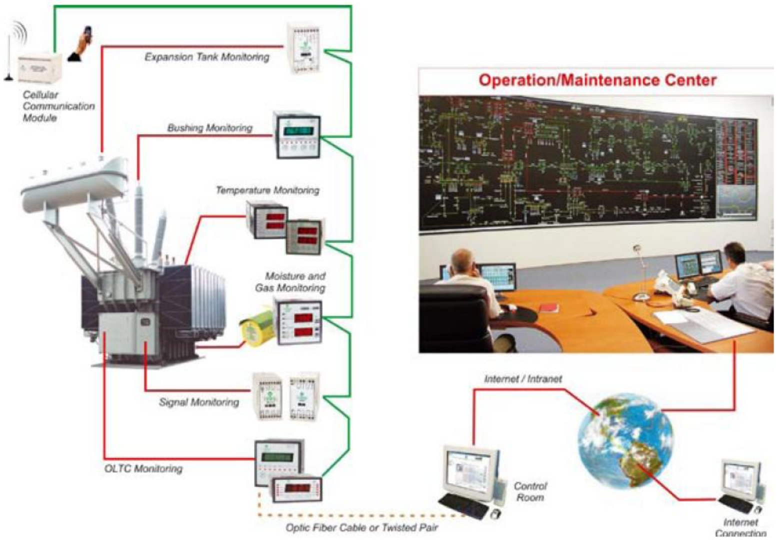

Figure 1 – Architecture of the monitoring system

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, because the devices are not intelligent ones, 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.

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 tank, 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. This characteristic of the decentralized architecture was proved in practice through several expansions in the years that followed.

One of those expansions was carried out in 2003, when intelligent sensors (IEDs) were added to the system for monitoring of capacitance and tangent delta of 230kV and 138kV bushings. A second expansion happened in 2005, when several gas-in-oil sensors already installed in transformers in other Eletrosul substations were added to the system through their Intranet.

IEDs	Data Acquired
Temperature Monitor	- Oil temperature - Hottest-spot temperatures - Load currents - Alarms and trips by high temperatures
Gas in Oil Monitor	- Hydrogen dissolved in transformer oil - Alarms by gas high/very high
Transformer Moisture in Oil Monitor	- Relative saturation (%) of water in transformer oil - Water content in transformer oil (ppm)
LTC Moisture in Oil Monitor	- Relative saturation (%) of water in tap changer oil - Water content in tap changer oil (ppm)
Membrane/Bag Relay	- Rupture in conservator tank membrane / bag
Voltage and Current Transducer	- LTC motor voltages - LTC motor currents - LTC motor active/reactive/apparent power
Temperature Transducer	- LTC oil temperature - Ambient temperature
Data Acquisition Modules	- Alarm contacts (buchholz relay, pressure relief device, oil levels, etc.) - Status of forced cooling groups - LTC in operation - LTC operation time
Bushing Monitor	- Bushings capacitance - Bushings tangent delta
Voltage Regulator Relay	- Phase voltages - Phase currents - Active/reactive/apparent power
Parallelism Supervisor	- LTC tap position - Selections local/remote, master/follower/individual and manual/automatic

Table 1 – IEDs associated to the monitoring system

2.2. Physical communication media

The physical media used for communication of IEDs with the monitoring server in the control room was a copper, shielded twisted pair cable. Even though optic fiber solutions were available and possible, at higher costs, the features of the RS485 communication standard and the previous experience with the same solution in a 230kV substation at Alumar [1] showed 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. The operation of the system has shown the twisted-pair solution satisfactory.

It is worth highlighting that, as alerted by Lavieri et. al. [4], essential in the success of this strategy is the fact that the IEDs used are devices developed specifically for the substation environment where they are being used. Devices 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 substation 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.

- 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.
    - Automatic warning messages by email in case of any abnormal condition.
- Monitoring functions:
    - Algorithm based data treatment
    - Mathematical model based data treatment
    - Diagnostic of transformer current condition
    - Prognosis of transformer future condition
    - Early stage defect detection.

3. MONITORING FUNCTIONS

More than a system for simple digitizing of sensor measurements, a monitoring system must be able to transform these data into useful information for transformer maintenance, which are equipment condition diagnosis and prognosis.

In order to comply with this function the monitoring system is equipped with the so called "Engineering Module", which contains the algorithms and mathematical models for diagnostics and prognostics.

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.

The monitoring system in operation is equipped with the monitoring items described below.

3.1. Insulation Useful Life

This monitoring function performs the calculation of the estimated insulation loss of life due to the thermal aging of cellulose, in accordance with the load and temperature undergone by the transformer. This calculation is also corrected according to the water content in the cellulose, which is obtained from the engineering model in item 3.4.

It also calculates the average loss of life rate in a past period which is representative of the transformer average operation condition and extrapolation of the theoretical remaining life cycle for the insulation.

3.2. Forecast of Final Temperature Gradient

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 trip is detected, in addition to informing the time remaining before alarm and/or trip temperatures are reached.

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 trip 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.
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.

3.3. Gas in Oil

Performs on-line supervision of the concentration of hydrogen dissolved in oil. Since hydrogen is a gas generated in almost 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 of 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. Water in Oil and in Insulation Paper

The presence of moisture in the insulating paper reinforces the effects of the thermal degradation of the insulation in proportion to the water content.
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 or bag that prevents the contact of the oil with the open environment, and in addition to this, also monitors the water dissolved in oil content.
Besides that it performs calculation of percent water content in insulation paper considering the moisture balance between oil and cellulose. Therefore the monitoring system performs on-line supervision of the level of water dissolved in oil and water in paper, issuing alarms for both, high content levels in oil and/or in paper.

3.5. Bubbling Temperature

Besides reinforcing the effects of thermal insulation aging, water in paper can change to the vapor state in the presence of high temperatures thus causing the risk of a dielectric failure. The temperature level necessary to cause this phenomenon will be as lower as the water content in paper is higher.
For this reason the monitoring system uses the result of water in paper calculation (item 3.4) to determine the temperature necessary for bubble formation. In case the winding temperature (hottest spot) gets close to that value the system will trigger a warning.

3.6. Cooling System Efficiency

Adequate cooling of transformers is essential in their safe operation without accelerated life cycle losses for the insulation when operating under heavy load regimes. Therefore, it is essential that the cooling system operates perfectly, removing the heat generated by the losses.
The monitoring of cooling system efficiency is performed by comparing the measured top oil temperature to its expected value, calculated as a function of the ambient temperature, load current and forced cooling groups in operation.
In case the measured temperature is much above its expected value the system will trigger a warning.

3.7. Load Tap Changer Temperature Differential

All failure statistics for power transformers point to the 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.
Under normal operating conditions the load tap changer is not an important source of heat compared to the transformer's active part. This way, the LTC oil temperature will generally follow the transformer oil temperature.
Some types of failure, however, can cause abnormal heat generation in the LTC, thus making its temperature remain higher than the transformer's oil temperature. In this event the monitoring of the LTC to transformer temperature differential will trigger a warning, allowing for corrective actions before the defect evolutes to a severe failure.

3.8. LTC Motor Torque

The load tap changer represents one the major sources of failures in power transformers. The reason for that, as already mentioned, is the fact that the LTC is a mechanical device, based on mobile parts. This way, mechanical failures in the load tap changer can bring about consequences ranging from transformer unavailability to severe dielectric failure.
In this event the torque developed by the LTC motor will present variation compared to its normal behavior. Therefore, the monitoring of motor torque allows for the detection and identification of mechanical problems in the LTC.

3.9. Load Tap Changer Operating Times

Failures of mechanical nature in the 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 load tap changer operating times supervises the time required to perform the tap change in each of its operation, issuing alarm in case this time deviates from the times observed during regular behavior of the equipment.

3.10. Load Tap Changer Maintenance Assistant

The Load Tap Changer Maintenance Assistant helps in supervising regular load tap changer wastage, 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 load tap changer maintenance:

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

3.11. Forced Cooling 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. 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, becoming it partially unavailable.

For this reason, normal fan wastage 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, bearings).
The Forced Cooling Maintenance Assistant allows fan operation times to be known accurately, thus avoiding these 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.

4. EXPERIENCE WITH INSTALLATION AND OPERATION OF THE SYSTEM

4.1. Characteristics of Decentralized Architecture

The experience with the operation of the monitoring system in Itajai substation allowed for the confirmation of some characteristics of the decentralized architecture used:

- Modular System – Expansion of the Monitored Variables.

  In 2003, two years after the monitoring system started operation, the on-line monitoring of bushings capacitance and tangent delta were added. This was achieved by just installing the new intelligent sensors (IEDs) and connecting them in parallel with the serial communication network RS485 already in place. There was no need for changes in the existing communication and data acquisition infrastructure. A software module was also increased for recording of the new variable in data banks and exhibition on the screen.

- Open System – Integration of Third Part Sensors

  Eletrosul had in its substations several transformers with gas in oil sensors already installed. Taking advantage of the monitoring system being an open system, in 2005 it had those sensors integrated using the company's Intranet as communication path. Although the existing sensors had a serial communication port, it operates with a proprietary protocol. A specific communication driver was developed for the sensors to allow the integration with the monitoring system.

- Open Software – Inclusion of User's Functions

  The analysis of gas-chromatography test results is carried out in Eletrosul using a proprietary methodology developed with the company's experience with this technique. As the monitoring software has also an open architecture it allows for the inclusion of user specific functions like that. The DGA analysis methodology of Eletrosul was thus added to the monitoring software.

4.2. Serial communication with copper cable

Because it was one of the first commercial systems to operate in on-line monitoring 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 RS485 with copper cables in substations with this voltage level. This objective was fulfilled when they operated satisfactorily even in very adverse electromagnetic interference conditions found in this kind of facilities, which has been attested by these nearly six years of operation of the system.

5. CONCLUSIONS

The power transformer monitoring system in Itajai substation was, together with the system in the Reduction Substation of Alumar, one of the first ones to operate commercially in Brazil. The operation of this system for six years, since December 2001, has allowed checking the reliability of the decentralized architecture selected, which is mainly obtained by using intelligent sensors (IEDs) specifically designed for the aggressive environment found in electric substations.
Based on this initial experience Eletrosul began specifying the delivery of on-line monitoring systems for the new power transformers bought since then. The specification of these new systems includes, among other requirements, their total integration with the basis of the Itajaí system.
The operation and evolution of the monitoring system in Itajaí used some of the main characteristics of the decentralized architecture. Along time the monitoring of new variables was added, as well as third part sensors located in distant substations. It was used also the characteristic of being an open software to include in it the Eletrosul proprietary DGA analysis algorithm.

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