Application of On-line Monitoring Systems in the view of Maintenance Engineering of Eletrobras Furnas

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Abstract – **The increasing demand for greater reliability and continuity in electricity supply, confirmed by new applications of electricity, such as electric cars, for example, are reflected in industry regulations, which provide heavy financial penalties in case of interruption of supply or even unavailability of transmission equipment, even if scheduled in advance.**

Thus, the maintenance engineering faces the challenge of providing increased reliability and availability of high voltage equipment simultaneously with the virtual elimination of equipment shutdowns for testing and reduced maintenance costs.

In this scenario, the systems for on-line and continuous monitoring and diagnostic of high voltage equipment condition, during normal operation, are essential tools for more effective and intelligent management of those assets, by enabling predictive maintenance, based on actual condition, to replace preventive maintenance, based on time.

This paper presents the experience of Eletrobras Furnas with the operation and maintenance of on-line monitoring systems composed of sensors, communications and data processing software for diagnostics and prognostics of high voltage equipment condition, mainly power transformers.

The centralized and decentralized architectures for sensor data acquisition are analyzed and their characteristics, advantages and disadvantages are presented, as well as case studies resulting from a large amount of monitoring systems deployed in field.

***Keywords* – Online Monitoring, Diagnostics, Prognostics, Predictive Maintenance, Sensors, Software, Transformers.**

I. Introduction

Electricity is becoming increasingly more essential to society, which leads to an increasing demand for greater reliability and continuity of supply. New applications of electricity, such as electric cars, for example, confirm this trend.

These needs are reflected in industry regulations, which provide heavy financial penalties in case of interruption of supply or unavailability of transmission equipment, even if scheduled in advance.

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II. TYPICAL TOPOLOGY OF ON-LINE MONITORING SYSTEMS

Typically, on-line monitoring systems for power transformer adopt the topology shown in the block diagram in figure 1, where the following main components can be defined:

- Variable Measurement – Measurement of the different variables considered to be important in order to know the condition of the equipment performed via sensors and/or transducers, in general located on the transformer. If the architecture adopted is Centralized, there will also be a measurement concentration device (PLC).
- Data Transmission – Consists in transmitting data from measurements taken by sensors, obtained in the preceding stage, to the stage of data storage and processing, using the most convenient physical medium for the purpose.
- Data Storage and Processing - Data Storage and Processing for readings issued by sensors targets obtaining useful information for asset maintenance and management, such as diagnosis and prognostics of the state of the different subsystems and overall condition of the transformer. This also avoids overloading maintenance engineering with a high volume of data, not always easily interpretable.
- Information Availability – For monitoring systems to deliver their objectives, information related to the state of

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the equipment must be made available to the different interested parts, while simultaneously maintaining data integrity and access security.

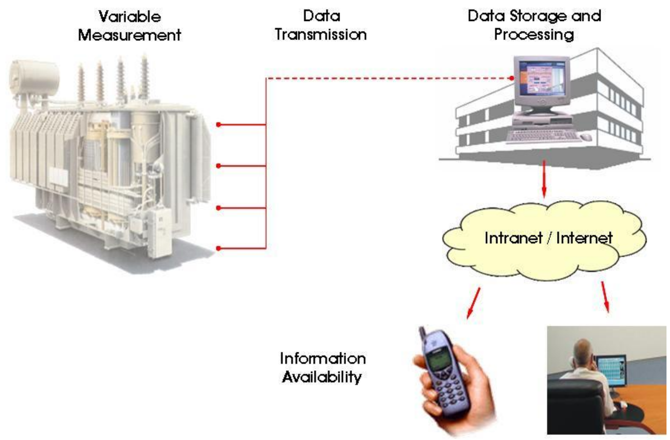

Fig. 1. Typical Topology of a Transformer Monitoring System

A. Variable Measurement

Furnas specifies the on-line monitoring system for power transformers to measure the following variables as a minimum, using adequate sensors:

- Ambient temperature
- Oil temperature
- Hot-spot temperatures
- Load tap changer temperature
- Condition of conservator bag/membrane
- Water content and relative saturation in transformer oil
- Bushing capacitance and tangent delta
- Hydrogen in oil
- Load Currents and Voltages
- Tap changer position
- LTC motor currents and voltages
- Transformer oil level
- Tap changer oil level

B. Data Transmission

Transmission of data from the sensors to the substation control room can be achieved via a range of different means of communication, according to the requirements of the type of architecture deployed in measuring the variables.

In systems with centralized architecture for measuring variables, optic fiber cables are usually deployed.

In systems with decentralized architecture, on the other hand, in addition to the option for optic fiber cabling, it is possible to use RS485 serial communication standard cables, with the advantage of the lower costs and shorter installation times, thus contributing to reducing costs and increasing financial feasibility for monitoring systems in small scale transformers.

Other communication options can also be studied, depending on the characteristics of the facility, such as for example, dedicated radio links or Wi-Fi wireless networks.

If the data storage and processing is performed by a computer in the substation control room, the data transmission network can be connected directly to it. However, if the computer is in another remote facility, sensor data transmission is done via company's intranet.

C. Data Storage and Processing

The data supplied by the sensors located on transformer body, both raw readings and those supplied resulting from the pre-treatment of the data, are received by a computer, which can be located in the substation control room or at a remote location, running the monitoring software.

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 must be equipped with an "Engineering Module", which contains the algorithms and mathematical models for diagnostics and prognostics. Some of the main diagnostic functions that can be executed by the monitoring software are:

- Insulation Loss of Life
- Forecast of future temperatures
- Overload capability
- Cooling system efficiency
- Cooling Maintenance Assistant
- Gas in oil evolution trend
- Water in Oil and in Paper
- Bubbling temperature
- Free water formation temperature
- Load tap changer temperature differential
- LTC motor torque

D. Information Availability

In order to create availability of the information from the monitoring system, the computer used to run the monitoring software will be connected to the company Intranet. In order to allow access to the monitoring system without the need to install specific software in all remote computers, the user interface must be an internet browser, without any add-ons.

In addition, in order to avoid the need for ongoing follow up of the system, which would lead to major time consumption (and respective cost) for maintenance engineering, the monitoring system must send automatic alert messages if any abnormality is detected. Alerts can be sent by email or by SMS text messages on cell phones, according to definitions previously recorded on the system.

III. Maintenance Engineering Experience

Eletrobras Furnas generates 10% of the electricity in Brazil, in 15 hydroelectric and two thermal power plants with installed capacity of 10,000 MW, and has about 19,000 km of lines that transmit more than 40% of the electricity consumed in the country, in an area that accounts for 81% of national GDP. The transformation capacity is approximately 102 GVA, with 642 transformers distributed in 49 substations with voltage levels up to 750 kV AC and ± 600 kV DC.

The great responsibility of the company in the Brazilian electrical system and the wide geographic area served made Furnas to be one of the pioneers in the application of on-line monitoring systems for transformer, with the purchase of monitoring systems composed of sensors and data processing software for more than one hundred transformers and shunt reactors in the last 10 years.

A. Architectures of monitoring systems

The transformer on-line monitoring systems acquired by Furnas can be grouped in two types of architecture:

- Centralized systems: using a centralizing element located in the body of the transformer, usually a PLC (Programmable Logic Controller), to effect the acquisition and preprocessing of the measurements of various sensors installed in the transformer and relay them to the monitoring software in the substation control room.
- Decentralized systems: using smart sensors type IED (Intelligent Electronic Devices) in the transformer, which transmit their measurements directly to the monitoring software, eliminating the centralizing element.

The topology of each of these architectures can be observed in figures 2 and 3.

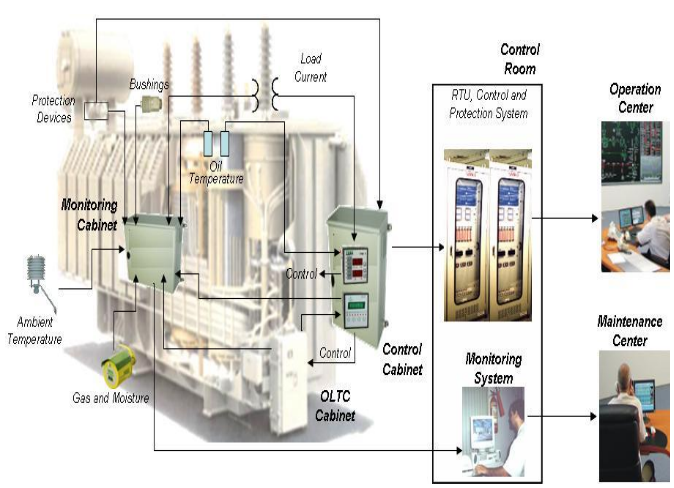

Fig. 2. Topology of system with Centralized architecture

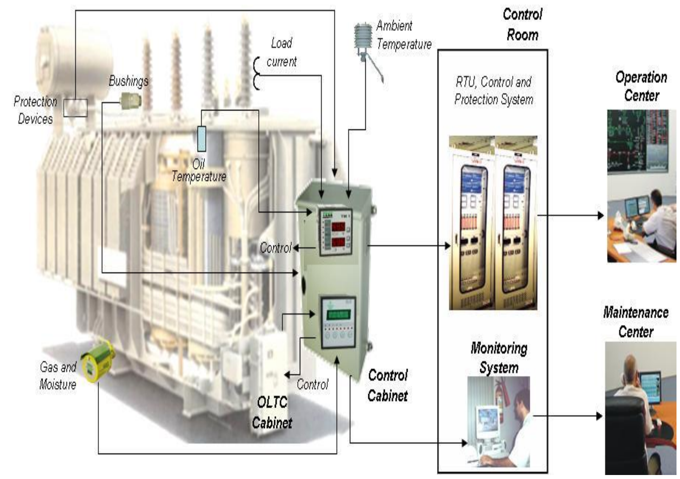

Fig. 3. Topology of system with Decentralized architecture

B. Results obtained with Centralized and Decentralized Architectures

The experience of Furnas maintenance engineering with the operation and maintenance of monitoring systems using centralized architecture has shown that these systems have high incidence of defects, generating high workload for the maintenance engineering and maintenance crews in the field, to the point of total ineffectiveness of the monitoring system.

The same behavior was not observed in systems with decentralized architecture, which has shown good reliability and availability. It soon became apparent that this difference in results is due to the inherent characteristics of each of these architectures, shown in Table I.

TABLE I:
CHARACTERISTICS OF CENTRALIZED AND DECENTRALIZED ARCHITECTURES [1]

Centralized Architecture	Decentralized Architecture
PLC concentrates information received from all sensors and sends them to the monitoring software.	Decentralized system, where sensors are IEDs (Intelligent Electronic Devices) that send the information directly to the monitoring software.
Centralizer element (PLC) is an additional failure point for the system	There is no centralizer element, thus eliminating a possible failure point.
Sensors must be dedicated to the connection to the PLC, resulting in the need for eventual duplication of sensors and additional costs for monitoring systems.	Existing IEDs in control and protection systems can be integrated to the monitoring and data acquisition systems, avoiding the costs of additional sensors.
Failure in PLC may lead to loss of all functions offered by system.	Failure in one IED leads to loss of just a part of the functions – other IEDs continue in service.

Centralized Architecture	Decentralized Architecture
Centralizer element (PLC) represents additional costs in installing, programming and maintenance for the system.	There is no centralizer element – eliminating additional costs.
Centralized system, expansions and maintenance more difficult.	Modular system, making expansions and maintenance easier.
Typical maximum PLC operating temperature is 55ºC [2]. Installing at the transformer body is not advisable.	Operating temperature -40 to +85ºC, suitable for installing in yard on main equipment.
Installation recommended in control room – large number of connection cables between device and yard.	Typical installation on main equipment, in yard – only serial communication for link to control room.
Typical insulation level 500V – not suitable for high voltage substation environments [2].	Typical insulation level 2.5kV – designed for high voltage substation environment.
Generally tested for application in industrial environment [2].	Tested for the adverse conditions in substations according to international standards: electromagnetic compatibility, temperature, vibration
Serial communication ports do not tolerate surges, impulses and induction found in substation, mandating the use of optic fiber in communication with the control room – high installation cost.	Serial communication ports designed for substation environment, allowing deployment of twisted-pair cables for communication with control room – low set up cost. Allows optional use of optic fiber cabling, with self-powered external converters.
Usually operate using industrial communication protocols [2].	Specific communication protocols for deployment in power systems (time-stamp, clock synchronicity, etc.).

C. Successful case studies

Several successful case studies, described below, demonstrate the benefits of using on-line monitoring systems as long as built with the appropriate architecture. In all cases following a decentralized architecture is used.

1) Serra da Mesa Hydroelectric Plant:

Taking advantage of the modularity feature of the decentralized architecture a monitoring system was installed dedicated solely to on-line monitoring of bushings, with the possibility of future expansion.

Figure 4 shows details of the installation, which included the following equipment [3]:

- Three bushings 550 kV and three 245 kV in a bank of single phase auto transformers;
- Three 550 kV bushings on a bank of single-phase shunt reactors.

Fig. 4 – Details of bushing monitoring system installed [3]

A few months after being installed the monitoring system issued an alarm by an increase in the capacitance of the 550 kV bushing of the autotransformer phase A, as shown in Figure 5.

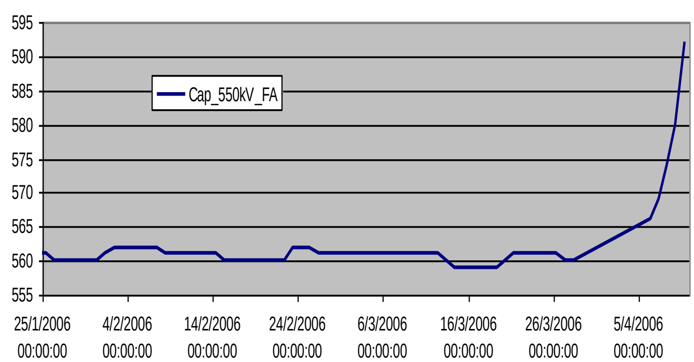

Fig. 5 – Capacitance increase of 550 kV bushing of autotransformer phase A

Due to this alarm, and the high rate of increase in capacitance, the bank was shut down for off-line measurements and oil sampling, which confirmed the existence of the defect. The DGA test found about 7000 ppm of acetylene, indicating imminent failure of the bushing.

Thus, the monitoring system prevented a catastrophic failure with possible fire and serious damage to the transformer [3].

2) Ibiúna Converter Substation:

Ibiúna is the substation where ±600 kV DC from HVDC transmission system of Itaipu hydroelectric plant is converted to 345 kV AC for supplying the Sao Paulo area, with installed capacity 7200 MVA distributed among 24 single-phase converter transformers (figure 6).

Figure 6 – View of a single-phase converter transformer

In the first stage of implementation of online monitoring the temperature supervision systems of all 24 converter transformers have been modernized, with the replacement of all original oil and winding mechanical thermometers by digital temperature monitors, as illustrated in Figure 7. As a result, the incidence of defects in the temperature monitoring system was reduced from an average of 7 defects /years to virtually zero, releasing the maintenance staff for other tasks and reducing maintenance costs and downtime of the transformer [4].

Figure 7 - Replacement of mechanical thermometers of the converter transformers for digital temperature monitors for the online monitoring system.

The monitoring system deployed includes also the online monitoring of capacitance and tangent delta of the direct current bushings on the converter transformers, a novel application in the world [5].

3) Campinas Substation:

With installed capacity of 1720MVA the substation Campinas is one of the most important for the transmission system of Furnas. To increase its transformation capacity, this substation received a new bank of single-phase auto transformers 345-138/13.8 kV 150 MVA with on-load tap changers, composed of two phases of manufacturing Jeumont / Vatech (France) 2001 and a phase Asea 1975.

Following the philosophy of migration of the preventive maintenance to the condition based maintenance the Jeumont transformers were specified by Furnas to be supplied already equipped with sensors and the Asea transformer was modernized with the installation of sensors for online monitoring. The sensors in existing and new transformers were connected to the online monitoring software, using the decentralized architecture [1].

In the commissioning stage, the monitoring system began online data acquisition and recording of measurements in historical databases, allowing local and remote access to information via Furnas intranet. At this stage, a fault occurred in phase B of the bank, which was removed from service by differential and overcurrent protections. Although the commissioning of the monitoring system was still incomplete, the data it had already acquired could be used after the failure to assist in the investigation of its causes.

Some of these data are shown in Figure 8, where we observe the behavior of ambient temperatures, oil and winding temperatures and percent loading, all in normal levels. In the same graph it can also be noted the temperature differential of the on-load tap changer, which had temperature slightly lower than that of the transformer, suggesting normal functioning of OLTC diverter switch.

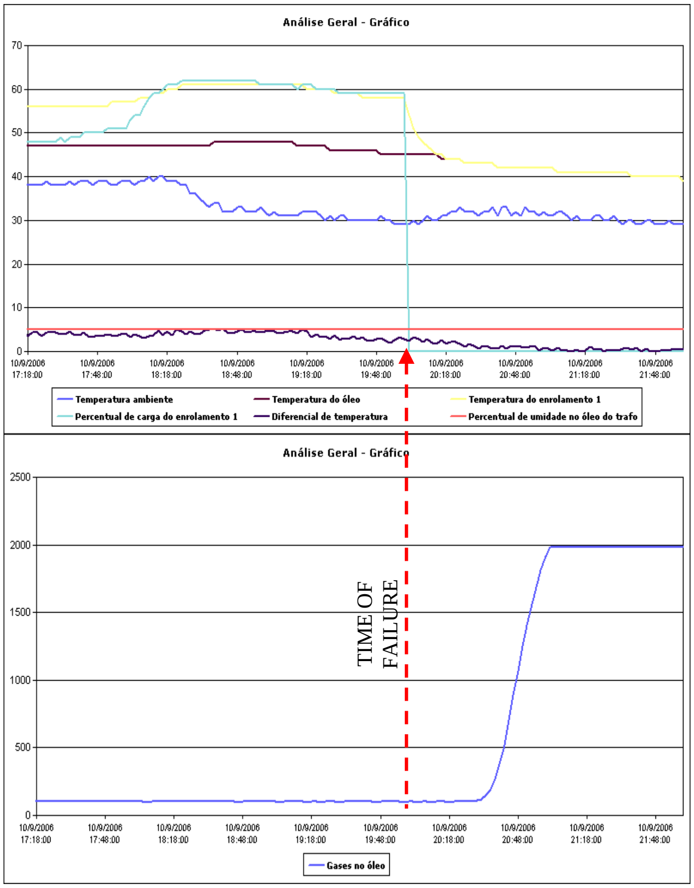

Figure 8 – Measurements of on-line monitoring system before and after the transformer failure [1]

It was only after the failure that the gas content in oil, which until then was stable, showed important elevation, reaching the full scale of the sensor.

Further investigation revealed that the origin of the failure was an internal varistor connected in parallel with the regulation winding [1].

This event demonstrated that the application of monitoring systems also allows the analysis of faults with a greater amount of information, providing a deeper understanding of the causes and / or the effects of failures, in order to determine more accurately the potential risks of specific transformer families and allowing also the improvement of the monitoring system itself.

In addition, the use of monitoring systems tend to facilitate the negotiations with insurance companies who see the possibility of avoiding the failures considered detectable, which can in principle reduce insurance premiums, since the refunds will be restricted to sudden faults or faults that are non-detectable with current technology [1].

This monitoring system was the first to be installed in Furnas using a decentralized architecture and is in successful operation ever since, helping to demonstrate the advantages of this architecture.

IV. Conclusion

The experience of Furnas maintenance engineering with the operation and maintenance of a large number of transformer online monitoring systems has shown that the architecture used to build the systems plays a decisive role for their reliability and ease of maintenance. The decentralized architecture based systems showed better results than those with centralized architecture, which had a high incidence of defects and require high maintenance burden.

The cases of successful use of systems based on decentralized architecture also demonstrated the importance of online monitoring systems to avoid catastrophic failures of equipment, increase equipment availability and reduce maintenance costs.

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VI. Biographies

Fabio Abreu Pinto was born in the city of Rio de Janeiro, State of Rio de Janeiro, Brazil on April 18 1969 and has been working with Eletrobras Furnas since 1991. He graduated in 1992 from Universidade do Estado do Rio de Janeiro - UERJ, in Rio de Janeiro, with an Electrical Engineering B.S. degree.

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Marcos E. G. Alves (M' 2007) was born in the city of Rio de Janeiro, State of Rio de Janeiro, Brazil, on July 15, 1975, and has been working with Treetech since 1992. He majored in Power Transformer Control and Monitoring, and he currently coordinates the Research, Development and Innovation department. He graduated in 2001 from the Universidade São Judas Tadeu, in São Paulo, with an Electrical Engineering B.S. degree, and in 2005 he concluded his Masters in the Energy and Automation area from the Universidade de São Paulo He is currently taking the course of study to obtain his Doctoral degree in Energy from the same university.