Group VIII Substation and Electric Equipment Study Group On-Line Monitoring of 345/138/13,8 Kv, 150 Mva AutoTransformer Bank with on Load Tap-Changers

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Abstract

In order to increase the substation's transformation capacity, Furnas substation in the city of Campinas, received a new bank of 345/138/13,8 kV, 150MVA, single-phase, autotransformers with on load shunt tap-changers, comprised of two phases manufactured by Jeumont/Vatech (France) in 2001 and one phase by ASEA, in 1975.

Moving with the general trend of migration from preventive to predictive maintenance, the Jeumont transformers were specified by Furnas, using a contract amendment, for delivery already equipped with sensors and on-line monitoring systems. This scope also included the modernization of the ASEA phase by installing sensors for monitoring and substitution of electromechanical devices with intelligent electronic devices (IEDs).

The benifits achieved by operating with this on-line monitoring system in the field will be shown, including the finding of a defect in one of the phases of the bank during the period when the system was being installed, with a part of the data capture system already in operation.

We will also show how the readings obtained in the implementation phase helped in investigating the causes for the occurrence.

KEY WORDS

Transformer, online monitoring, Diagnosis, Prognosis.

1.0 Introduction

With 1720 MVA of installed capacity, the Campinas substation is one of the most important for FURNAS's transmission system and is also the venue of one of the company's four regional operating centers responsible for the trunks that feed the greater São Paulo metropolitan area.

In order to increase the substation's transformation capacity, Furnas substation in the city of Campinas received a new bank of 345/138/13,8 kV 150 MVA single-phase, autotransformers with on load shunt tap-changers (OLTCs), comprised of two phases manufactured by Jeumont/Vatech (France) in 2001 and one phase by ASEA in 1975.

The current energy market scenario in the world has led companies to operate in an unprecedented competitiveness context, forcing on them a constant search for higher efficiency, better delivery quality, and lower costs. Together with this general trend, there has been the migration from preventive to predictive maintenance, which caused FURNAS to order the Jeumont transformers with sensors and on-line monitoring systems.

In addressing this specification, the autotransformer bank was equipped with a Treetech SIGMA on-line monitoring system. The scope also included renovation of the Asea transformer by installing sensors and IEDs for on-line monitoring.

2.0 Topology of the On-Line Monitoring System

The Sigma on-line monitoring system is comprised of three main parts as listed below:

Data capture

Means of communication

Data storage, treatment, and availability.

2.1 Data capture

Capture of readings with transformers in regular operation is done by way of sensors that can be connected using two different main types of architecture:

Architecture based on a centralizer element located on the transformer casing, usually a PLC , and

A decentralized architecture, based on IEDs located on the transformer casing.

In choosing the architecture to use with the Sigma system, the inherent features of each of these two types were taken into account as shown in Table 1.

Table 1 – Feature Comparison Between Centralized and Decentralized Architectures

Centralized Architecture (PLCs)	Decentralized Architecture (IEDs)
Centralized system – the PLC concentrates the information coming from every sensor and sends it to the next superior hierarchical level.	Decentralized system where sensors are IEDs that send information directly to the next superior hierarchical level.
The 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 for connection to the PLC, thus leading to eventual duplication of sensors and additional costs in monitoring systems.	IEDs, already part of control and protection systems, can be integrated into the data capture and monitoring systems, thus avoiding costs with additional sensors.
Failure in the PLC leads to loss of all system functions.	Failure in IED leads only to loss of part of the functions – the remaining ones continue in operation.
The centralizing element (PLC) represents additional costs in installing, programming, and system maintenance.	There is no centralizing element – additional costs are eliminated.
Centralized system- more difficult to implement expansions and maintenance.	Naturally modular system, facilitating expansions and maintenance.
Typical maximum operating temperature 55ºC [3]. Installing close to main equipment (for example, transformers) is not advisable.	Operating temperature range -40 to +85ºC, suitable for installing in substation yard on main equipment.
Installation recommended in control room – large number of cables linking to yard.	Typical installation is on main equipment, in yard – only serial communication (twisted pair or optical fiber) to link with control room.
Typical insulation level 500 V – not suited for high voltage substation environment [3].	Typical insulation level 2.5 kV – designed for high voltage substation environment [.
In general, tested for deployment in industrial environments [3].	Tested for adverse conditions of outdoor applications in substation yard environments in accordance with IEC standards: electromagnetic compatibility, temperature, vibration.
Serial communication ports do not support surges, impulses, and induction existing in substations, forcing the deployment of optical fiber for communication link to control room – high installation cost.	Serial communication ports designed for substation environment, allowing the use of twisted pair cables for communication with the control room – low installation cost. Allows optional use of optical fiber with self-powered external converters.
Usually operates with industrial communication protocols [3].	Specific communication protocols for use in power systems (timestamp, clock synchronicity, etc.).

Upon analyzing both, the choice was made for decentralized architecture, given its advantages. A few IEDs are placed on the casing of the transformer, as shown in figure 1, while others are located in a common panel for the bank. In the case of phase A, the ASEA transformer received a retrofit with IEDs being installed to replace the former electromechanical devices, such as mechanical thermometers for oil and winding temperatures. IEDs with control functions were also integrated into the monitoring system. The full list of IEDs installed in each point can be seen in Table 2.

Figure 1

In those cases where third party sensors could not be integrated into the system by way of serial communication because of not being intelligent devices or because the manufacturer does not offer open protocol functionality at serial ports, universal data capture modules were used which are capable of receiving multiple digital and/or analog signals, digitizing them and making them available on open protocol serial ports.

In this way, every sensor, intelligent or conventional, could be integrated into the monitoring system through a serial communication network using the means of communication described in item 2.2. Thus, the need to deploy a centralizer element on the casing of the transformer was avoided, simplifying the project and implementation, reducing initial cost and, most importantly, reducing the system's TCO (Total Cost of Ownership) in the same ratio as it increased its reliability and availability.

Table 2 – IEDs Associated with the Monitoring System

Local	IEDs	Data Acquisition
Transformer	Temperature Monitor	Oil temperature, winding temperature, load current alarm ,and shut down due to excessive temperature
	Gas-in-Oil Monitor	Hydrogen dissolved in oil alarms for high and very high gas content
	Moisture Monitor	Relative saturation (%) of water in oil content (ppm)
	Membrane/Bag Relay	Rupture of conservation tank membrane / bag
	Voltage and Current Transducer	Tap changer motor voltage, current, and power of tap-changer motor
	Temperature Transducer	OLTC radiator in/out temperatures of oil
	Data Capture Modules	Alarm contacts (Buchholz relay, relief valve, oil levels, etc.). State of forced ventilation groups, OLTC in operation, OLTC operation time
Common Panel	Bushing Monitor	Bushing capacitance and tangent delta
	Voltage and Current Transducer	Transformer phase voltage, current, and active/ reactive/apparent power
	Temperature Transducer	Ambient temperature
Control Room	Parallelism Supervisor	Position of tap-changer, state of options including local/remote, master/slave/individual, and manual/automatic

2.2 Means of Communication

The SIGMA monitoring system allows communication of data from data capture devices (IEDs) to the stage of storage and treatment in the control room to be performed through different means of communication. On this transformer bank a number of them were used.

The IEDs located in the station yard, both directly on the casing of transformers and in the bank's common panel, were linked together in a standard RS485 network using shielded, twisted pair, metallic cables. This deployment, along with several others deploying this communication standard in high voltage substation environments, showed the feasibility of its use in substation environment with totally satisfactory results.

On the bank's common panel, this RS485 network is connected to an optical converter from which a pair of optical fiber cables goes to the rack of the monitoring system in the control room. In this rack, the optical signal is converted back into an electrical signal and connected to the system server. IEDs located in the substation control room are linked directly to the server in the RS485 standard.

2.3 Data Storage, Treatment, and Availability

The data supplied by the IEDs located on the transformers in the common panel for the bank and in the control room are received by a computer located in a rack in the substation control room where it is employed in the monitoring software.

This software's main functions can be grouped in two classes: data digitizing functions,associated with simple data availability and storage, and monitoring functions for taking simple data and transforming it into useful, meaningful information for maintenance purposes, as shown below.

- Data Digitizing Functions:
  - On-line display of readings, alarms, and states
  - Storage of readings, alarms, and states in history databases
  - Inquiry of readings, alarms, and states stored in history data bases in the form of charts and tables
  - Local and remote access to system
  - Automatic sending of notices via email in the case of abnormality.
- Monitoring Functions:
  - Algorithm-based data treatment
  - Mathematical model based data treatment
  - Obtention of diagnosis of the transformer'scurrent state
  - Obtention of prognosis for future state oftransformer
  - Detection of defects while still in their early stages. Monitoring functions are detailed in item 3 below.

3.0 Monitoring Functions

More than just a digitizing system for the data obtained from sensors, a monitoring system must be able to transform this data into meaningful information for maintenance applications, which are the equipment state diagnostics and prognostics.

In order to deliver this function, the monitoring system implemented has an engineering module which contains and runs the algorithms and mathematic models for diagnostics and prognostics.

Similar to what happens with the IEDs used in capturing readings, the system's monitoring functions are also organized modularly, which gives total freedom of choice in terms of the monitoring functions one wishes to install, in addition to facilitating future expansions by simply adding new software modules and their corresponding IEDs. The diagnostic modules used are described below.

3.1 Insulation Life Cycle

This module calculates the estimated lifetime loss of the insulation due to the thermal aging effect of cellulose according to load conditions, temperature, and water content in insulation obtained from the corresponding engineering module. It also calculates the average lifetime loss rate for a given period in the past that is representative of the median operating conditions of the equipment and extrapolates the time remaining to the end of the insulation's theoretical life cycle.

3.2 Gases in Oil

An on-line monitor measures the concentration of hydrogen dissolved in the oil. Since hydrogen is a gas generated in nearly every type of internal defect that may occur in a transformer, it is considered a key gas in defect detection. Once an abnormality has been detected, the monitoring system recommends performing gas chromatography testing in laboratory. Results obtained in these tests are then input into the system, and the system then issues an opinion based on analysis criteria generally accepted in the industry.

3.3 Moisture in Oil and in Paper

In a first stage, the monitoring system monitors ruptures of the expansion tank's rubber bag, issuing an alert in case of oil-air contact. At a second level, there is on-line measurement of water in oil content in ppm. Through this measurement, correlated to the equipement temperature readings, the percent water in solid insulation (paper) is calculated, considering the moisture balance between oil and paper. The percentage of water in paper is used in the functions of "Insulation Lifetime" and "Bubble Formation Temperature", and warnings are issued for high water content in oil and/or paper.

3.4 Bubble Formation Temperatures

In addition to exacerbating the effects of thermal degradation, the water present in the insulation paper may move to the vapor state in the presence of high temperatures, increasing the risk of insulation failure. The temperature required to cause this phenomenon becomes lower as the water in paper percentage content rises. For this reason, the monitoring system uses the result of the calculation of water in paper content (item 3.3) to also calculate the temperature required to initiate bubble formation. If the temperature of the winding (hottest point) comes close to this value, the system issues an alarm.

3.5 Efficiency of the Cooling System

Adequate cooling for the transformer is vital in to its safe operation and to prevent accelerated insulation lifetime loss in the presence of high loads. Therefore, it is essential that the cooling system operates correctly, efficiently dissipating the heat generated.

Efficiency of cooling is monitored by comparing actual oil temperature to an expected value as a function of the ambient temperature, load current and the cooling stage in operation. If the temperature measured is above that expected, the system issues a low efficiency warning.

3.6 Tap-Changer Temperature Differential

In normal operating conditions, the tap-changer is not a significant source of heat as compared to the active portion of the transformer. The temperature of the tap changer oil usually matches the temperature of the transformer oil. However, a few types of failures can cause generation of heat in the tap-changer, causing its temperature to be higher than the transformer's. Monitoring the difference between transformer and tap-changer temperatures is used to issue a warning, allowing action to be taken before the failure becomes severe.

3.7 Torque of Tap-Changer Motor

The on-load tap-changer is an equipment with moving parts. Failures with mechanical origins occurring on the tap-changer may cause problems of different magnitudes, starting with equipment unavailability and going all the way to severe dielectric failures. In these cases, the torque developed by the tap-changer motor will eventually show deviations in relation to its normal behavior, so that monitoring them allows eventual mechanical problems to be spotted and identified.

3.8 Tap-Changer Operating Times

As a complement to the "Torque of Tap-Changer Motor" function, this function tracks the time required to perform the tap change in each tap change operation, issuing an alarm in case this time shows a deviation in relation to the times observed during the equipment's regular behavior.

3.9 Maintenance Wizard for OLTC

Based on the number of changes and on the time in service of the on-load tap-changer, the tap-changer maintenance wizard delivers meaningful information and alerts useful in helping determine necessary maintenance. The wizard uses data such as sum of current switched and number of operations performed to calculate current contact thickness, equipment in-service time, daily average contact wear,, estimated time to reach minimum contact thickness, and time to next maintenance.

3.10 Forced Cooling Maintenance wizard

By tracking the exact operation times of the fans, the Forced Cooling Maintenance Wizard delivers meaningful information and alerts useful as maintenance help, such as fan and pump in operation times, records of motor operation times, average in operation times and time forecast to next inspection or maintenance.

3.11 Specialist Module

This module is an additional tool to be used in treating information. While the other modules point to the existence of a possible or actual problem, the specialist module cross matches information, coming from both sensors and mathematical models, with the common objective of determining the probable cause for the problem, recommending correction action,, and giving the prognosis for future complications in case the defect is not corrected.

In order to deliver these functions, a specialist system is used. An artificial intelligence technique comprised of a set of rules is used to make an hypothesis as to the probable cause of the existing condition and issue a recommended response. This set of rules is flexible, and can be changed by the user to match his/her own experience.

This way, the specialist modules offer users an overview of the state of the equipment without having to browse across the system's different functionalities. For this reason, the specialist module is always the first screen displayed when the monitoring system is accessed.

3.12 Simulation Module

In general, the temperature reached by the equipment is the limiting factor in transformer loading. The simulation module allows users to check for hypothetical loading conditions, the estimated resulting temperatures, and the associated loss of lifetime. There are two simulation modes available:

Based on actual conditions, the current load and temperature readings are used as a starting point for the simulation. Users merely input new load figures and obtain as output the oil and winding temperature evolution curves.

Based on hypothetical conditions — all simulation conditions are input by users for a 24-hour period including evolution of ambient temperature and load and cyclical loading or not. The outputs delivered are the oil and winding temperature curves for the 24-hour period in addition to the daily percentage loss of lifetime and estimated remaining lifetime.

In all simulations, users can modify the cooling command (off, automatic, or manual) and the temperatures for actuation and hysteresis of cooling.

4.0 Data Availability

Due to the large geographical area serviced by Furnas and the large number of transformers used, one of the main requirements specified for the monitoring system was remote access to information. In order to allow this access from any of its facilities, the means of communication chosen was the existing company intranet.

In order to do this, the monitoring server located in the control room is connected to the intranet with access to data, information, diagnosis, and prognostics performed exclusively through pages in HTML without the use of any plugin, so that they can be opened on any standard internet browser. This makes installing any special software in the company computers unnecessary, which avoids a high volume of work for the company IT team in addition to making the access independent of the operating system used.

In addition, with transformers in regular operating conditions, which is expected to be the vast majority of the time, the monitoring system will remain static, and only issue warnings or diagnosis of defects.

In order to avoid the need for an ongoing monitoring of the system by the maintenance team, which would result in a major waste of their time, the monitoring system has been equipped with a mechanism for automatic sending of emails in the event of any abnormality. To this end, the email addresses of staff responsible for maintenance are previously registered on the system.

5.0 Results Obtained

As early as in the commissioning phase, the monitoring system started to capture data on-line and records of measurements taken were stored in the history database, allowing local and remote access to information via FURNAS Intranet.

Still in commissioning stage, a failure occurred in phase B of the AT4 bank, which was removed from operation by the conventional protections (differential and overcurrent). In spite of the still incomplete commissioning of the monitoring system, the data captured by the system was used after the failure event to help investigate the causes.

Some of this data is shown in figure 3 where we can see the behaviors of ambient, oil, and winding temperatures, in addition to the percentage loaded, all of which were l considered normal. In this same chart we can also see the differential of the on-load tap-changer temperature, which indicated the temperature of the tap-changer as slightly inferior to that of the transformer, which suggests regular operation for the OLTC diversion switch.

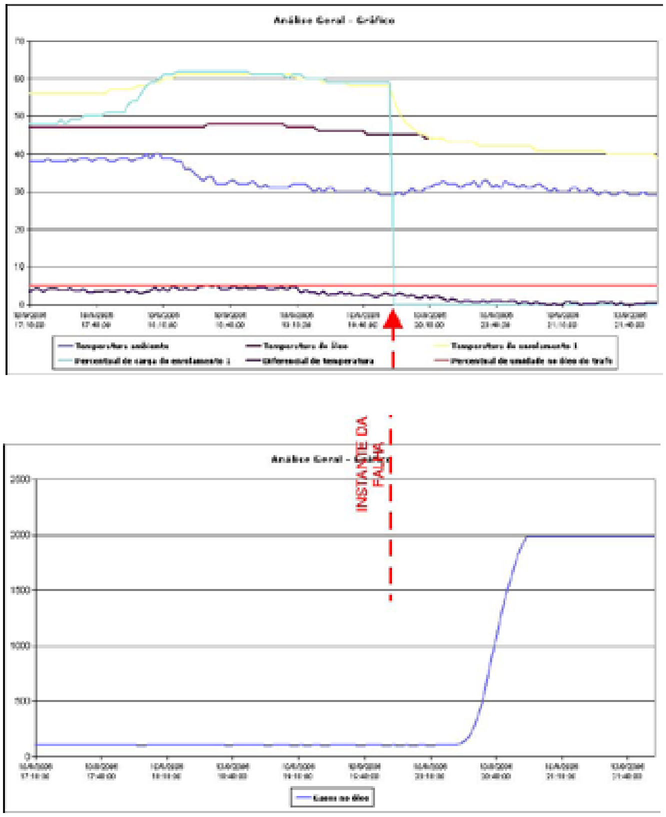

Figure 3 – Measurements of gases and other variables before and after the failure

Only after the failure did the gas–in-oil content, which to that point had remained stable, show a high rise, reaching the sensor's end of scale. Possible reasons mentioned for this were:

The failure was sudden, beginning and ending with the failure of the insulation in a very short period of time;

The defect was of a type that did not generate hydrogen before the total failure of the insulation;

The defect generated hydrogen in small quantities, insufficient to sensitize the sensor used in this specific phase because the sensor is sensitive to CO and the content of this gas in the transformer was much higher than that of hydrogen. Because of this the sensitivity in measuring hydrogen is reduced, masking the measurement of small value changes in hydrogen content;

The defect occurred at a point without direct contact with the transformer oil, so that the gases generated did not reach the on-line sensor.

Later investigations revealed that the origin was one of the internal overvoltage limiter devices (Zenox), used in parallel with the regulation winding. This proved that the last hypothesis presented above was true, however without discarding the possibility of it being a sudden failure.

6.0 Conclusions

On-line power transformer monitoring is a tool that helps in migrating from time-based maintenance (preventive maintenance) to equipment condition based maintenance (predictive maintenance). In this way, maintenance resources, both financial and human, can be deployed in an optimized way, avoiding unnecessary interventions and detecting possible defects while still in their initial stage. In order to do this, the monitoring system must have data treatment capability, generating diagnostics and prognostics, in addition to featuring some sort of warning mechanism in case an abnormal condition is detected, for example, through sending e-mails or SMS messages.

Application of the monitoring systems also allows analysis of possible occurrences with more information, affording a greater knowledge of failure causes and effects, in order to determine even more accurately potential risks of transformer failures and allow ongoing enhancement of the monitoring system.

In addition, the use of monitoring systems tends to facilitate dealing with insurance companies that perceive the possibility of predicting and avoiding failures.. This may lead to reduced insurance premiums, since claims will be limited to sudden failures or those still not detectable with existing technology.

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