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EXPERIENCES WITH WIRELESS TRANSFORMER MONITORING SYSTEM INSTALLED BY THE MANUFACTURER AND OPERATED AT STRATEGICALLY IMPORTANT LOCATIONS OF THE MEXICAN GRID

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SUMMARY

Several wireless on-line monitoring systems have been installed on 230 kV, 60 MVA transformers inside Mexico City, and one Mexican utility has operated a 33.6 MVA transformer at a high ambient-temperature location with similar wireless monitoring-system for more than one year. Besides, advanced sensors and dedicated monitoring equipment have been implemented on transformers at the nuclear power plant.

Design of the monitoring system was based on perceived needs of the HV network operators, namely alarms or early warning of oncoming faults, and the transformer condition-assessment that allows the operator to make an optimum use of transformer capacity in terms of permissible overload.

Besides, the monitoring system has to determine the number of oil pumps and ventilators for transformer operating conditions, i.e. the load current, hot spot temperature, moisture-content in cellulose and amount of gases dissolved in oil.

The monitoring system has been composed of sensors that are intelligent electronic devices (IED) that record pertinent physical quantities, the modular intelligent electronic devices are connected to RS 485 communication bus to avoid the use of centralized equipment; specialized software that derives the required information from the sensor records, and wireless signal transmission that uses the mobile telephone system (employing General Packet Radio Service (GPRS) protocol) and makes the processed data available on Internet.

In general, the operating experience gathered for more than one year of service in Mexican network has confirmed satisfactory performance of the monitoring system. Transformer overload has been weighted against the solid insulation loss of life. The cooling system control has saved energy by switching off the oil pumps and ventilators that were not needed during the low load periods. Such factors as a lower air density at the high altitude affect the transformer cooling efficiency, are taken into account when setting the signal processing algorithms. Degradation of HV bushing insulation has been indicated in time to prevent an in service failure.

Planned improvements of the monitoring system include recording of short-circuit current in the transmission network and lightning as well as system-generated overvoltages. Such records will enable the transformer owner to schedule diagnostic off-line procedures, such as

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checking the winding mechanical integrity by Frequency Response Analysis, and the insulation condition by dielectric polarization methods, such as Frequency Domain Spectroscopy.
The operating experience and description of the on-line wireless transformer monitoring system installed by manufacturer and operated on important locations of the Mexican grid is presented and some important aspects of on-line monitoring systems are discussed.

KEYWORDS
Power transformers, on-line monitoring, wireless monitoring, diagnostic.

1 Introduction.

On line monitoring and diagnostic of power transformers has attracted considerable attention for many years [1]. The main objectives are to prevent forced outages, indicate acceptable overload, assess the remaining insulation-life and reduce maintenance costs. To achieve these goals, the monitoring system manufacturers must follow strategies, which are in line with the interests of transformer owners.
Several wireless on-line monitoring systems have been installed on 230kV, 60MVA transformers inside Mexico City, and one Mexican utility has operated 33.6 MVA transformer at a high ambient-temperature location with similar wireless monitoring-system, for one year. Besides, advanced sensors and dedicated monitoring equipment have been implemented on transformer at the nuclear power plant.
Design of the monitoring system was based on perceived needs of the HV network operators, namely alarms and warnings of an on-coming fault, bushing power-factor time-trends, moisture content in oil, overload current, temperature of windings and oil [2,3]. Such information allows the dispatcher to make an optimum use of transformer capacity in terms of permissible overload conditions. Operational experience of the monitoring system has been gathered for one year, and indicates reliable data acquisition and transmission. Further work is carried out on transformer models, which are employed to derive easy to interpret messages from the sensor readings.

2. Signal acquisition, transmission and processing

An effective installation of the on-line monitoring system requires suitable communication links for alarms and data to be transmitted to the system operator, or maintenance engineers. A stand-alone modular system, using sensors that are intelligent electronic devices (IED) has been implemented and is presented in this paper. The modular IED's are connected to RS485 communication bus, to avoid the use of centralized equipment. Data from sensors installed on the transformer are transmitted by a wireless system that uses cellular-telephony network and employs GPRS (General Packet Radio Service) protocol. Finally, sensor readings are transmitted via Internet (web 2.0) to the remote Internet Data Center (IDC), where data are processed by the specialized diagnostic-software.
The load current is used in conjunction with oil temperatures to derive winding and insulation hotspot temperatures as well as over-heating time. The load current is also needed for tap-changer contact-wear calculations, over-current blocking of tap-changer operation and cooler efficiency monitoring and control. For transformers with more than two windings, the load is recorded on each winding.
A sensor of moisture content in oil provides data needed to evaluate water-content in transformer solid insulation. An oil level sensor installed in all separate oil-filled compartments reveals leaks and potential environmental threats. A special sensor detects perforation of the air-bag in the oil-conservator.

Control of the transformer cooling system is an important function of the monitoring system. The monitoring system switches on appropriate number of oil pumps and ventilators for the current load conditions, oil and ambient temperature.

Partial discharge (PD), winding frequency response, fast transient monitoring and bushing monitoring require a broad-band connection to the bushing tap. To facilitate this connection, the capacitor-type bushings shall be provided with an appropriate tap coupler. Preferably, designed according to IEEE C57.19.01. This coupler is also used to monitor system voltage. Precautions are taken to prevent damaging voltages that may appear on the tap under both working and impulse conditions.

In general, an operational experience gathered for more than one year of service in Mexican network has confirmed satisfactory performance of the monitoring system. The cooling-system control saves energy by switching off the oil pumps and ventilators that are not needed during the low-load periods. Such factors as a lower air density at the high-altitude affect the transformer cooling efficiency, and are taken into account when setting the monitoring system algorithms.

The existing monitoring system can be improved and expanded by addition of the on-line gas-in-oil analysis, recording of short-circuits in the transmission network, as well as lightning and system-generated over-voltages. Such records will enable the transformer owner to schedule off-line diagnostic procedures, such as checking the winding mechanical integrity by Frequency Response Analysis, and the insulation condition by dielectric polarization methods, e.g. the Frequency Domain Spectroscopy or Polarization and Depolarization Current.

3. The monitoring system

The wireless monitoring system installed by the transformer manufacturer and operated on medium-power transformers at different locations of the Mexican network has revealed a satisfactory operational experience. A few network transformers were equipped with the basic monitoring system, but transformers at the nuclear power-plant required a special attention and have been monitored for such parameters as number of particles in oil, content of seven gases dissolved in oil, as well as partial discharge charge and phase of appearance.

The monitoring system is composed of two modules: signal acquisition and processing. They include:

1. Acquisition module:
   a) Bushing monitoring
   b) Moisture in oil monitoring
   c) Temperature monitoring
   d) Oil conserver bag monitoring

   Besides, three optional sensors can be included, but some of them have not yet been connected to wireless signal transmission system:

   e) Counter of particles suspended in oil
   f) Monitor of seven gases dissolved in oil
   g) Partial Discharge detector

2. Signal processing module:
   a) Insulation Ageing
   b) Water content in paper
   c) Cooling Efficiency
   d) Final Winding-Oil rise
   e) Load Simulation – present conditions
   f) Load Simulation – hypothetical conditions.

Four 60 MVA, 230 kV and one 30 MVA, 115 kV transformer have been equipped with the monitoring system structured to the requirements of the Mexican utility.
Specialized software packages based on the transformer thermal model analyze the recorded data and predict the loss of transformer technical life, assess condition of HV insulation, signal the time to inspect OLTC, to dry and filter transformer oil and to perform off-line test of bushings.

4. Architecture of the monitoring system

The basic concept hinges on remote access to the recorded, processed and archived data, as well as to the alarms, which are available on Internet to the password holders. These crucial signals can be displayed on personal computers, palms, and mobile telephones that have access to Internet. Communication between the sensors and data acquisition module is ensured by RS 485 bus. Further data transmission uses mobile telephony network that is largely immune to interference and considerably faster than hardwired systems.

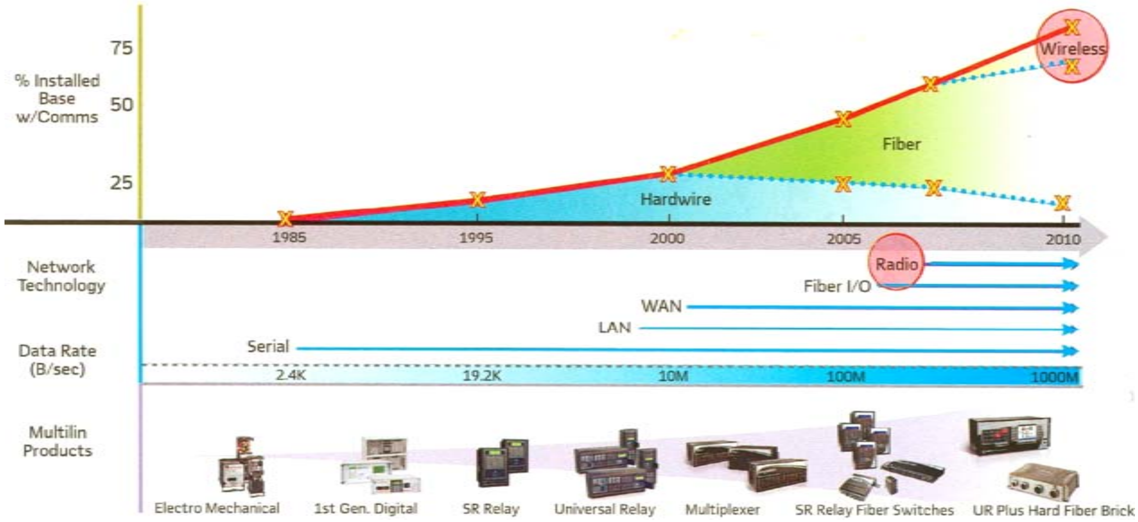

Figure 1. Progress of data-transmission performance over last 15 years. Trend of change of the implemented: wireless, fiber-optic and hardwired systems (upper curve). Data transfer rate of radio, fiber-optic, and hard-wired systems: Wideband Area Network, Local Area Network and serial interface. Evolution of hardware used by these different transmission systems (lower graph) [12].

The wireless data transmission is more suitable to implementation in HV switchyards where heavy equipment is moved on access roads that cross the hardwire or fiber-optic ducts to the control building, and broadband, high-intensity electromagnetic-field is produced at every opening of HV disconnect switch. The wireless-system is virtually immune to perturbations induced or conducted by HV transients notorious in the switchyards, since it uses the very high-frequency, mobile telephone communication system.
Raw data acquired by the sensors are processed by the IDC that warrants the continuous operation and security of data.

5. Sensors and records of processed data

Transformer load-current and oil, as well as ambient temperature are measured by standard equipment. Status of oil pumps and ventilators is obtained the same way, and transmitted on the RS 485 bus. These data are processed to derive the hot-spot temperature according to the IEEE standard procedure.

Figure 2. Schematic presentation of the wireless monitoring system. The sensors installed on the monitored transformer are of IED (*Intelligent Electronic Device*) type, and are directly connected to the short communication bus RS 485. Then, GSM (*Global System for Mobile Communication*) mobile-telephone transmitter sends them to the remote IDC (*Internet Data Center*) using GPRS (*General Packet Radio Service System*) protocol.

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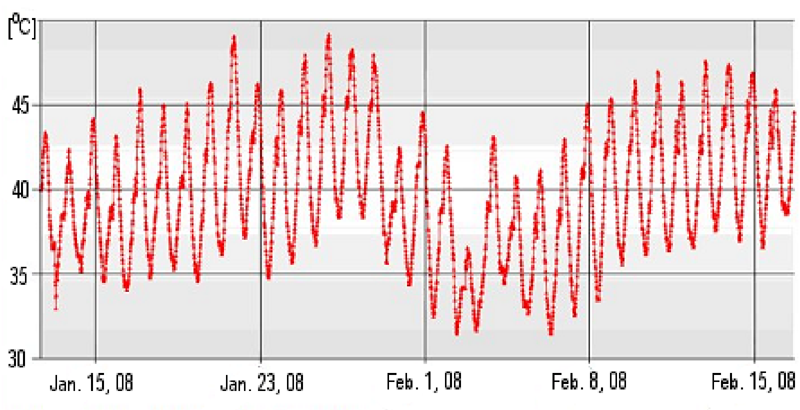

Figure 3. Thermometers record oil and ambient temperature. Winding temperature recorded for one month on 60 MVA, 230/23 kV transformer at CFE Cartagena substation. The winding temperature is derived from the top and bottom-oil as well as ambient temperature.

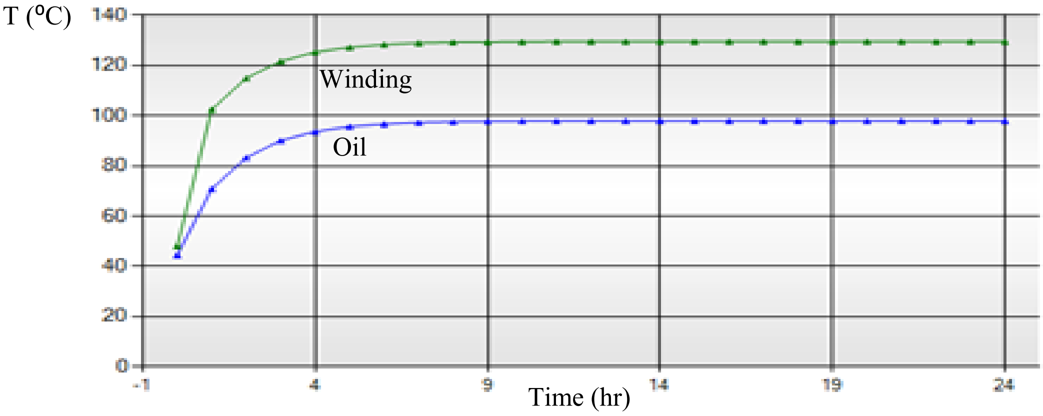

Figure 4. On-line monitoring software simulation of oil and winding temperature in case of 130% transformer over-load from present transformer load condition. Winding and oil temperatures increases to a stable level after approximately 7 hours.

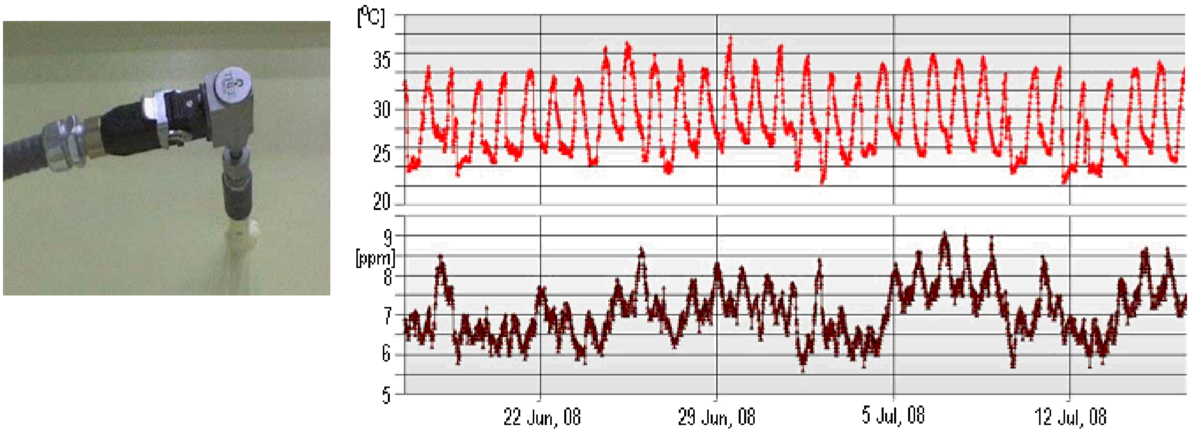

Figure 5. Sensor of water content in oil detects relative humidity of oil expressed in percents. Record of oil temperature and water content in oil expressed in parts per million (right graph).

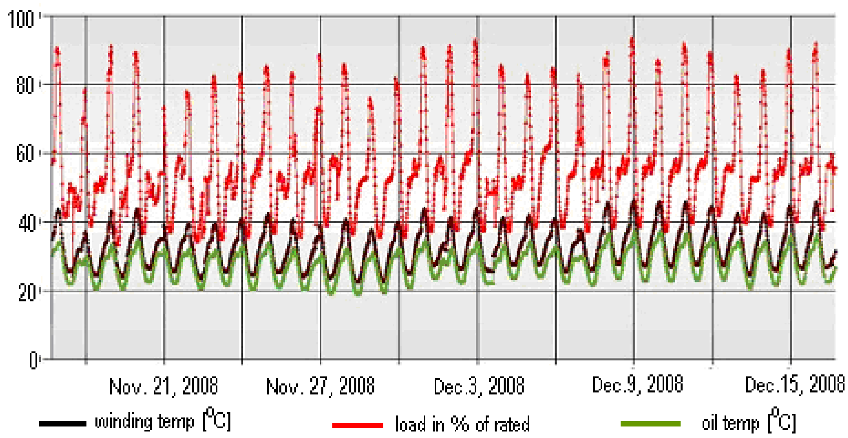

Figure 6. Transformer load expressed in percent of the rated load, winding and oil temperature. Ageing-rate of transformer solid-insulation depends on oil temperature and water content in cellulose [4,7]. Moisture content in solid insulation is derived from the readings of water content in oil and oil temperature. Thermal model of transformer determines the rate of cellulose ageing based on the hot-spot temperature and water content in solid insulation [8].

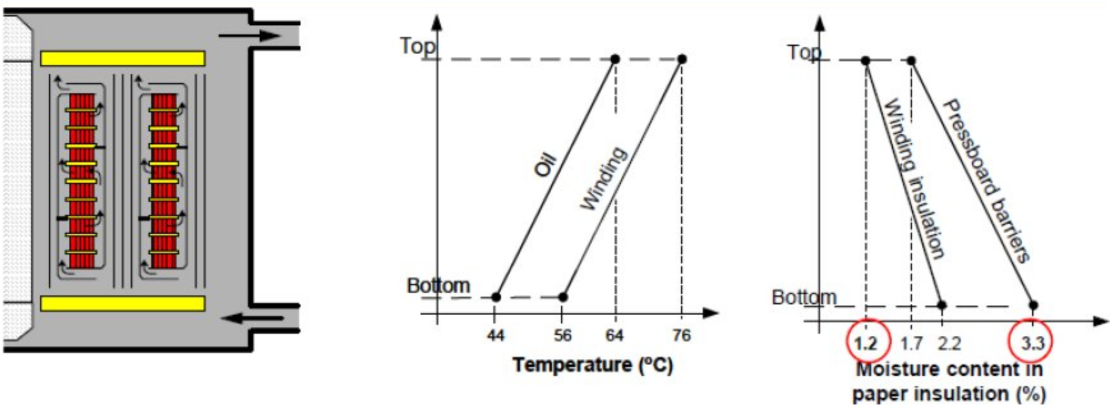

Figure 7. Thermal model of transformer accounts for heat transfer within the tank, as well as heat removal by the cooling system. A dynamic temperature distribution is determined by: the top and bottom-oil temperature, the load current, cooling system performance and heat transfer time-constants.

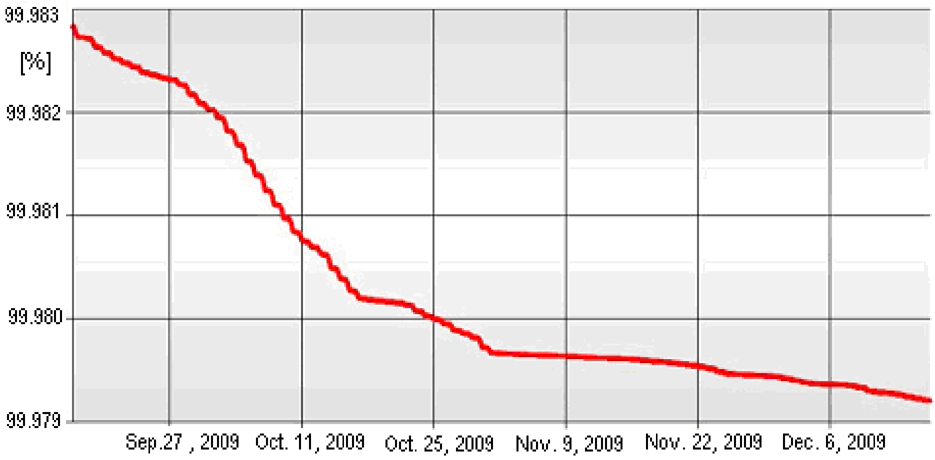

Figure 8. Remaining life of transformer solid insulation expressed in percent of the technical life assumed by the designer. Calculation based on the IEEE standardized formula.

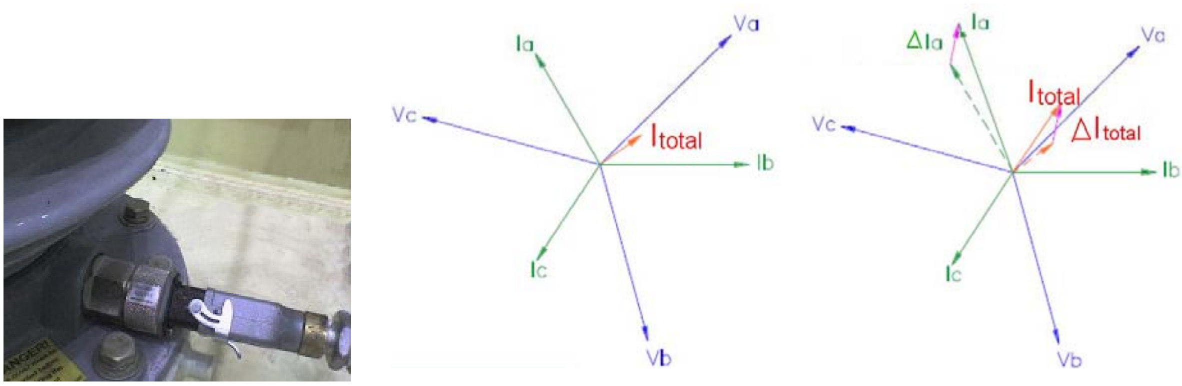

Figure 9. Bushing leakage current measuring connector (left). Example of vectors of leakage-current and phase voltage measured on transformer bushings. Current in phase A, as well as the total-current vector has changed its magnitude and phase angle. An increase of phase A leakage current ΔIa may indicate a short circuit of some aluminum foils in the bushing core.

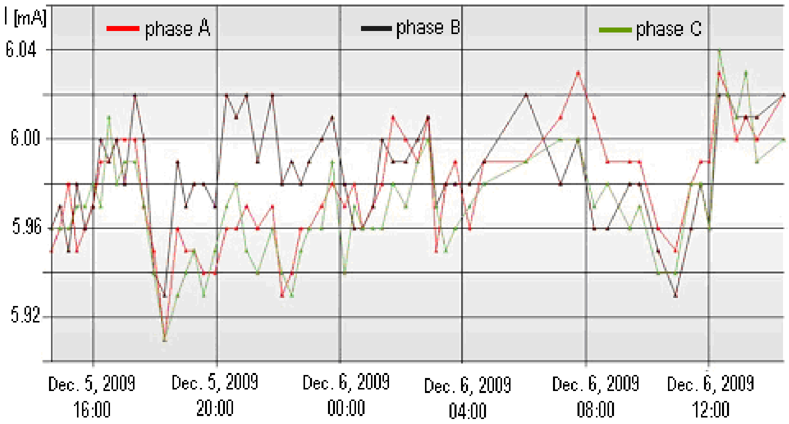

Figure 10. Leakage-current of three-phase bushings recorded for 24 hours. Scatter of instantaneously measured values indicates their strong dependence on bushing temperature. Load current in three-phase bushings may be unbalanced, as well as the bushing cooling by wind. A long-time record is required to evaluate the bushing condition, since temperature-induced changes of the leakage-current mask the short duration trend [9].

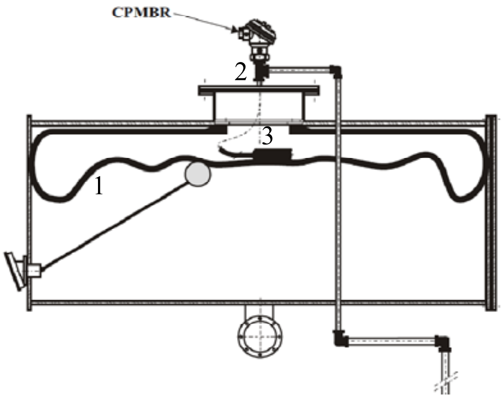

Figure 11. Air bag integrity sensor based on an optical detection of the bag contour. A light beam emitted by LED is directed by a light-guide that surrounds the bag. Perforated and collapsed bag changes the path of the light beam and initiates an alarm signal. 1) air bag, 2) light source LED, 3) light-guide and photo-detector.

6. Advanced signal acquisition and processing

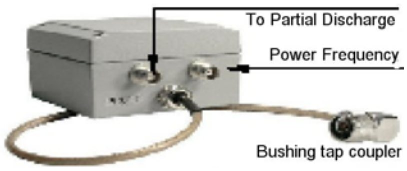

Figure 12. Partial discharge detector [10] has been attached to the bushing tap across a coupling-circuit that separates power-frequency voltage from a wide-band channel dedicated to partial discharge measurement.

Figure 13. Particle in oil counter passes a light beam through oil filled vessel, and indicates the number of particles that block the light beam. Histogram of particle size is provided by this counter, since it tallies the particles that fall within the range: 4µm; 6µm; 14µm and 24µm. The particle counter has not been equipped with the digital output signal compatible with RS 485 bus, and at this stage cannot be included in the wireless monitoring system.

7. Conclusions

- The high cost of transformer failure in service prompted utilities to implement a monitoring system that activates early-warning of oncoming insulation-failure, provides information on acceptable overload and resulting loss of insulation technical-life and prompts to carry on off-line diagnostic-test.
- In addition to the existing temperature and load current measuring devices, new sensors of: moisture in oil, insulation capacitance and dielectric loss factor, partial discharges, particles and dissolved gas in oil, have been developed with the digital output signal suitable to data transmission and processing
- Progress in data transmission speed and wireless communication enabled development of transformer monitoring system that uses the mobile telephone network to deliver the acquired data to remote control centers.
- Advanced thermal models of transformer have been developed to derive crucial parameters such as remaining technical life of cellulose insulation and hot-spot temperature from the sensor's output signal.
- Modular design of the monitoring system permits to select sensors and signal-processing algorithms appropriate to the transformer design and operating conditions.
- Research work is carried out to perfection the sensors and to improve processing algorithms in such a way to provide messages that assists the dispatcher to take right decisions and engineers in charge of transformer maintenance to assess its technical condition.

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