On – Line Transformer Diagnostics

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Abstract

For decades, transformer asset managers have sought ways to assess the general condition of electrical power apparatus and identify specific problems. Periodic off-line diagnostic tests still play an important role in industry. However, “continuous” or “on-line” monitoring can overcome some of the fundamental limitations of off-line tests while increasing performance and reliability of the monitored equipment.

As technology advances, additional continuous or on-line monitoring techniques are being developed and proven the in the field. This paper will present some newer on-line diagnostics methods and provide examples of monitoring and diagnostics for bushings and windings on transformers. These same techniques can be applied to high voltage current transformers, CCVTs and other equipment.

Bushings

Bushings are subjected to high dielectric and thermal stresses, and bushing failures are one of the leading causes of forced outages and transformer failures. Some studies have shown they can account for up to 40% of transformer failures. Data also shows that 52% of bushing failures are violent, in that there is an ensuing fire and collateral damage.

The two most common failure mechanisms are moisture contamination and partial discharge. Recent notices have been issued by bushing manufactures concerning the effects of corrosive sulfur in the bushing oil causing PD and bushing failure. Moisture can enter the bushing through deteriorated gasket material, cracks and loose terminals. Moisture will cause an increase in the dielectric losses and consequently an increase in power factor. As the deterioration in the bushing insulation continues there will be a breakdown in the capacitive layers and tracking will become apparent which produces partial discharges.

The method of detecting bushing insulation deterioration is well understood and traditionally off-line tests have been performed. The struggle facing the asset manager is that many of the failure mechanisms on bushings can occur very quickly, while some are temperature and voltage dependent. Offline testing at 10 kV and at ambient temperatures coupled with long intervals between tests can provided less than attractive results. On-line monitoring of the bushings provides data during all weather conditions, loads, and at rated voltage, with the same sensitivity as an off-line measurement.

It is evident that the online measurement of power factor and capacitance is a very useful and reliable diagnostic indicator. A very sensitive method for obtaining these parameters on-line is the sum current method. The basis of this on line monitoring method is to compare insulation characteristics of a three-phase bushing system. By vectorilly adding the currents from the test tap, one can determine the condition of the bushings. If the bushings have the same specifications and the system voltages are perfectly balanced, the sum current will equal zero. Of course in actual installations this is not the case.

Figure 1 shows a basic block diagram of a bushing monitoring system that uses the sum of currents method. During commissioning the null-meter is balanced to zero. The purpose of the balancing circuit is to take into account the differences in system voltages and bushing characteristics. As a defect develops the complex conductivity of the bushing insulation changes and the current and its phase angle in one of the phases also changes. Therefore, the null-meter will no longer be null. The amplitude of the change reflects the severity of a problem and the phase angle indicates which phase is experiencing the change.

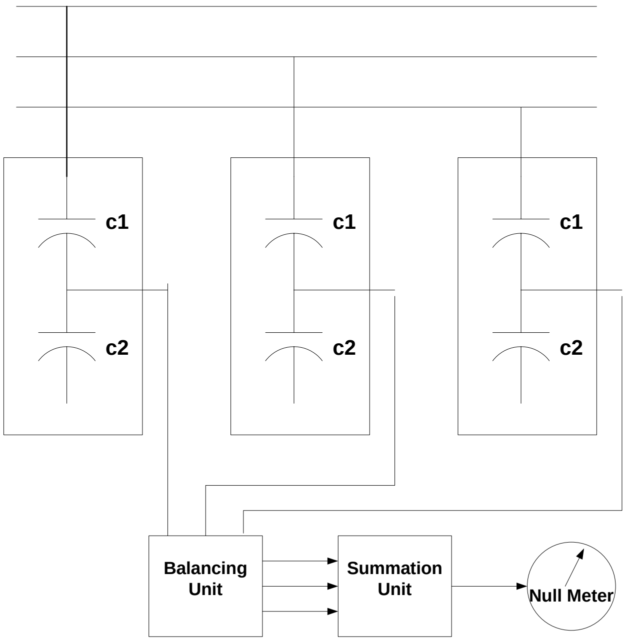


Figure 1
Block Diagram of the Sum of Currents Method

The change can be approximately represented by the formula under the assumption of a single defective phase:

$$\sum I = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta)^2 + \left({}^{\Delta C}\!/_{C_0} \right)^2}$$

where: $\sum I$ - Parameter Sum of Currents,

$\Delta \tan \delta$ - Tangent delta change,

${}^{\Delta C}\!/_{C_0}$ - Relative change in bushing capacitance.

Figure 2 shows a bushing monitor IED and a sensor installed in a bushing test tap. The system continuously monitors the power frequency current through the insulation of a 3-phase set of bushings as well as top oil temperature and load current.

(a) Bushing Monitor module with optional power supply and display

(b) Sensor installed in bushing test tap

Figure 2

Bushing Sensors

The test tap on bushing are normally grounded. If there were left open circuited, phase to ground voltage could build up at the tap and cause a bushing failure. Also, the instrumentation must be protected from system surges such as lighting strikes and transients. Bushing sensors should meet the following protection requirements.

1. Open circuit: Bushing insulation monitors usually have relatively low input impedance that keeps voltage at a tap at a safe level. If a tap is left open circuited, high voltage may build up on a tap according to capacitances C1 and C2/C3 operating as a capacitive divider. It is common to have capacitances C1 and C2 of a bushing of comparable values, therefore, if tap is open circuited the

voltage up to half of normal phase to ground operating voltage may be present on the tap pin providing both danger to operating personal and the bushing insulation. In such a case, the insulation of C2 is over stressed by a voltage that creates sparking inside the bushing, contaminating the bushing oil and finally contaminating the main C1 insulation with full phase to ground insulation breakdown. Therefore, a bushing sensor must keep “infinitely” safe rms voltage on the tap even if disconnected from an instrument or signal cable is unintentionally cut. There are several known solutions such as: installing a resistor or a capacitor in parallel to C2 bushing insulation or use another voltage limiting device inside a sensor body.

2. Switching and lightning strike surge protection: During normal operation, a bushing may see short duration surges created by a normal switching on a substation or a lightning strike in some proximity of the bushing. Such a surge may approach double operating voltage of a system and have duration for a portion of a microsecond to several tens/hundreds of microseconds. In an open circuited bushing tap, up to half of the surge may be present on the tap stressing C2 insulation over design limits. Surge protection of a sensor must keep the surge voltage at the tap at a safe level of several hundreds of volts. Some limiting devices inside bushing sensors do not provide protection against a surge while other do. As an example, a resistive load that is normally in the range of several hundreds of ohms to several kilo-ohms which forms C-R circuit with C1 capacitance. This circuit provides voltage limitation at power frequency but allows fast surge being almost fully applied to the C2 insulation.
3. Fail safe protection. This type of additional protection ensures shorting the bushing test tap to ground in case of all other protection layers fail.

The simplified protection circuit block-diagram is shown below in the figure 3.

Open circuit protection consists of four voltage limiting elements that keep rms voltage at the level of 18-20V. Current equalizing circuitry is added to ensure identical operation of each circuit and override individual difference of limiters. This protection is doubled to the requirements of the worst case scenario. Therefore only two limiters are sufficient for normal operation. Surge protection is designed to withstand up to fifty full BIL wave hits. Circuits are also double design requirements. The fail safe circuit will short to the ground bushing tap, if all other protection circuitry fails.

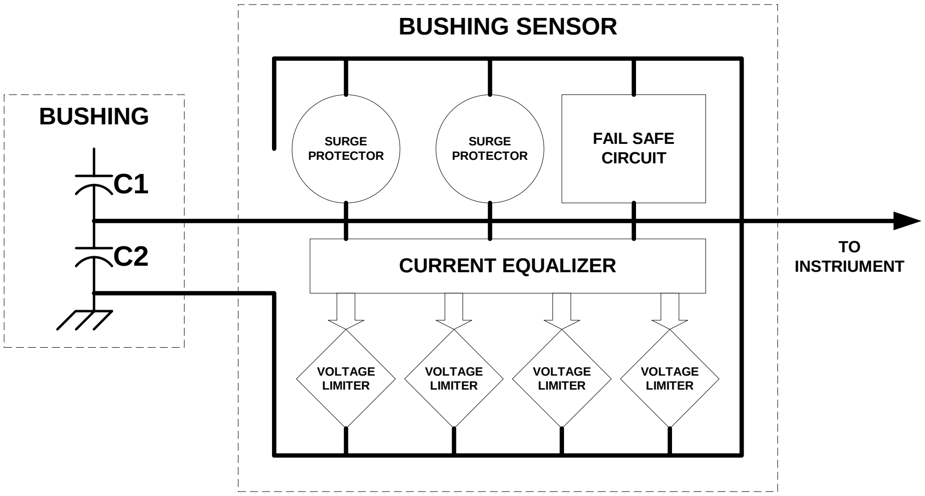


Figure 3 – Simplified protection circuit of a bushing sensor

Why Continuous Monitoring of Bushings

Some failure mechanisms of bushing occur very quickly. Others have voltage and temperature dependencies that are very difficult and time consuming to simulate during offline tests. If one is performing offline tests on bushings every three years, they are lucky if they find a problem. Bushing problems have been known to occur with a very short period of time measured in days to weeks.

Figure 4 shows the response of a known bad bushing over a 200 hour period with both voltage and temperature.. Trace 1 shows the response of the bushing at 25 °C and at 10 kV. This represents normal offline testing conditions. As one can see, the power factor readings are quite stable. Trace 2 shows the response of the same bushing a70 °C and 10kV. This represents the temperature dependency factor. As can be seen, the power factor is higher. Trace 3 represents the response at 25 °C and 70 kV. This response represents the voltage dependency of the defect. Trace 4 is the response at 70°C and 70kV.

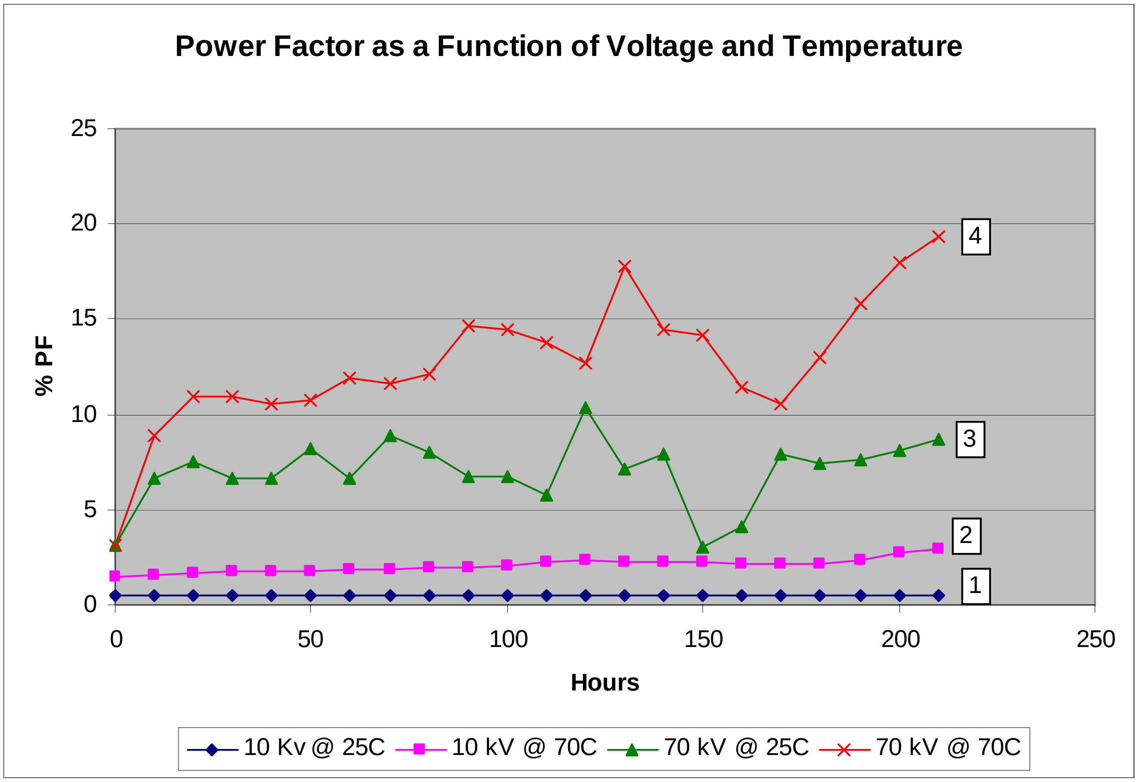


Figure 4

Response of Bushing Power factor as a Function of Temperature and Voltage
System Voltage Variations

System voltage behavior is one of the main contributors to method accuracy as a whole. This issue becomes very critical when the precision of 0.1% is required. A variation in system voltage (magnitude or relative phase shift between phases) creates an unbalance and may be interpreted as a capacitance or power factor change. Magnitude variation may be interpreted as capacitance change and phase shift variation – as power factor.

For changes in all phases the formulas should be changed to vector summations. The bushing monitor will react on asymmetric changes in system voltage only. All symmetric voltage changes will compensate each other (the same increase of all voltage magnitudes, for example, will not disturb a balance).

Therefore, accuracy of the method depends upon the statistics of the asymmetric voltage variations in the particular location and statistical data processing procedure. The effects of system voltage variations can be limited by using statistical processes and correlating these fluctuations with load current.

Diagnostics

The technology as originally introduced and implemented was focused on producing timely alarms and then suspected bushing should be further evaluated with additional off line tests. This part remains unchanged and Sum of Current parameter is a very reliable indicator of a dangerous trend in bushing insulation system. In addition, modern microprocessor based instrumentation allows for additional diagnostics performed on line while a unit is running. On line diagnostics provides additional valuable information and therefore advantages in maintenance strategy and as a result saves money. The main goal of on line diagnostics is to locate defective bushing, determine the predominant failure mode and finally predict timely critical insulation triggering shut down and bushing replacement. The diagnostics has three parts: time trend, temperature dependencies and defect identification. Defect identification requires determining the tangent delta and capacitance of all three bushings.

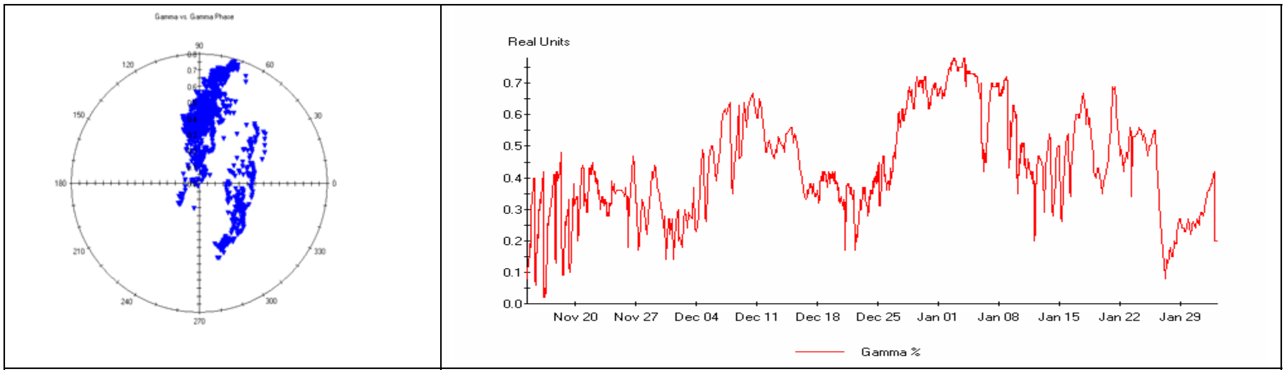
In the worst case of a single stand-alone unit installed on one three-phase transformer (or three single-phase transformers) five independent quantities can be obtained: three current magnitudes from the test tap and two independent phase angles between the currents. The number of variables is twelve, three of each: tangent deltas, capacitances, system voltage magnitudes, and phase angle between system voltage vectors. The situation partially improves by learning the statistical behavior of the system voltage at the particular location for a period of time and assuming that the tangent deltas and capacitances are known at the time and equal to their off line values. Based on the voltage behavior statistics we can then compensate for the change in the various quantities over time.

Practical Results

Case Study 1

A bushing monitor is installed on three single-phase transformers with all three having different bushings. The transformer operates in a peaking mode and generally has either full load or no load. Two clusters are observed in the phasor graph (Figure. 5a) reflecting different load modes: left – loaded and right – unloaded. Temperature variations during the observation period are from 15^0C to 64^0C. Figure 5b shows the variation in the sum of current rends over time.

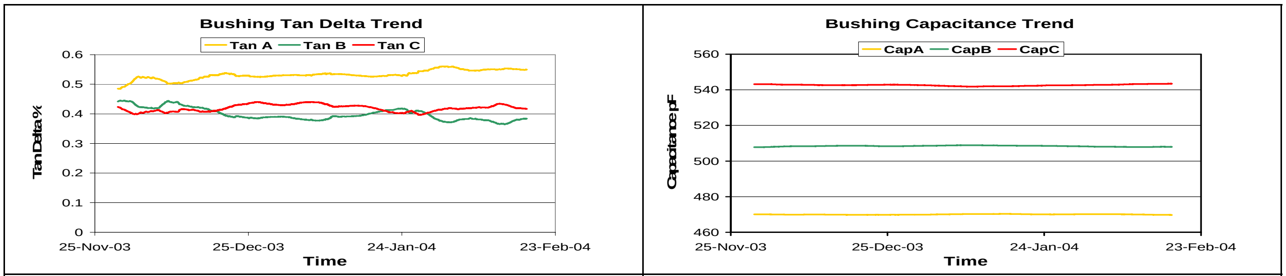
Figure 6 shows the trend of power and capacitance of each bushing. Phase A power factor is showing a slight increase which correlates with the DGA from that bushing (Figure 7) showing slight overheating.



(a) Two distinct clusters are shown due to load and temperature variations.

(b)Trend of Sum of Currents. Main variations are due to changes in the relative phase angles in phases. Alarm points are typically at 2 – 3 % with critical alarm set points at 5%.

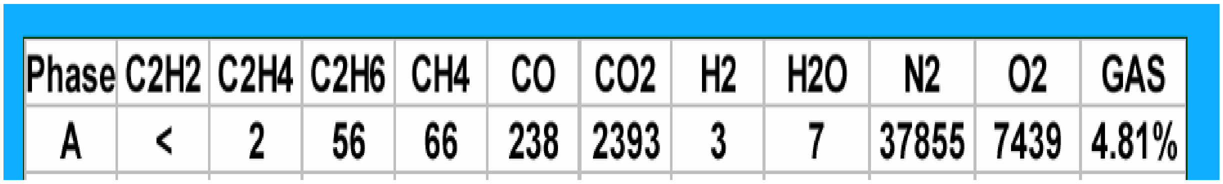
Figure 5



Note slight increase in Phase A Power factor. This correlated with DGA on bushing oil, which shows slight overheating.

Capacitance is fairly stable. Wide variation between bushing since each bushing is of a different manufacturer.

Bushing Power Factor and Capacitance Trend
Figure 6

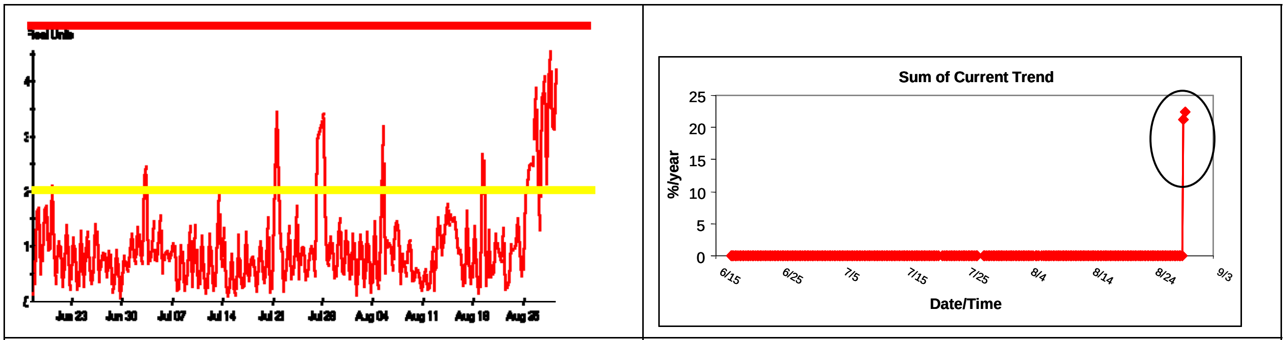


Phase	C2H2	C2H4	C2H6	CH4	CO	CO2	H2	H2O	N2	O2	GAS
A	<	2	56	66	238	2393	3	7	37855	7439	4.81%

DGA on Oil from Phase A bushing
Figure 7

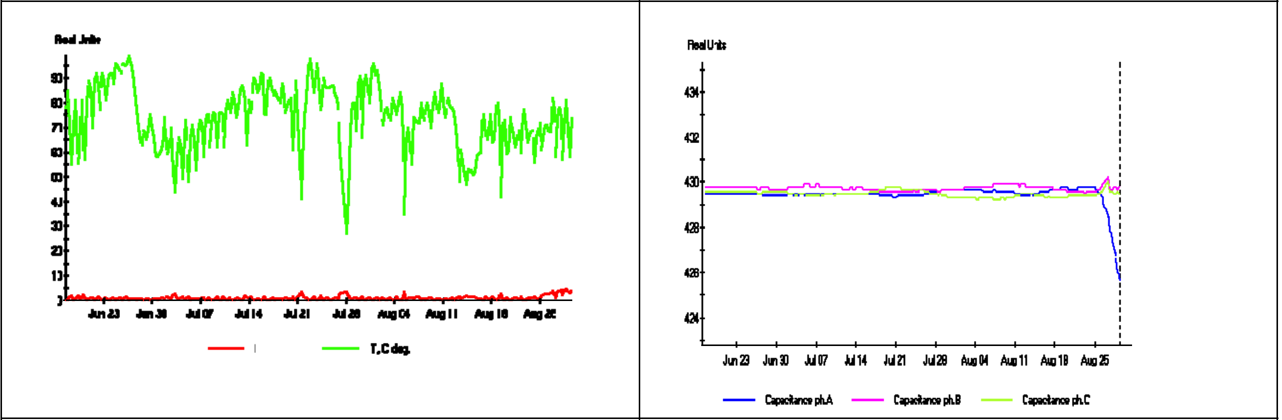
Case Study 2

A 650 MVA GSU unit catastrophically failed in August, 2005. In June 2005 a bushing monitor was installed on a 650 MVA GSU which subsequently failed catastrophically in August 2005. Unfortunately the monitor was alarming, but it was not connected to the Plant DCS system.



(a) Sum of Current Trend, very erratic and relatively high. Warning Alarms were being sent.

(b) Trend alarms were being sent hours before failure



(c) Sum of currents and temperature. Showing severe temperature dependency

(d) Phase A capacitance dropping very quickly

Data from 650 MVA transformer that failed catastrophically

Figure 8

Figure 8 shows data from this transformer. Magnitude Alarms, trend alarms and high temperature dependencies all indicated near term trouble.

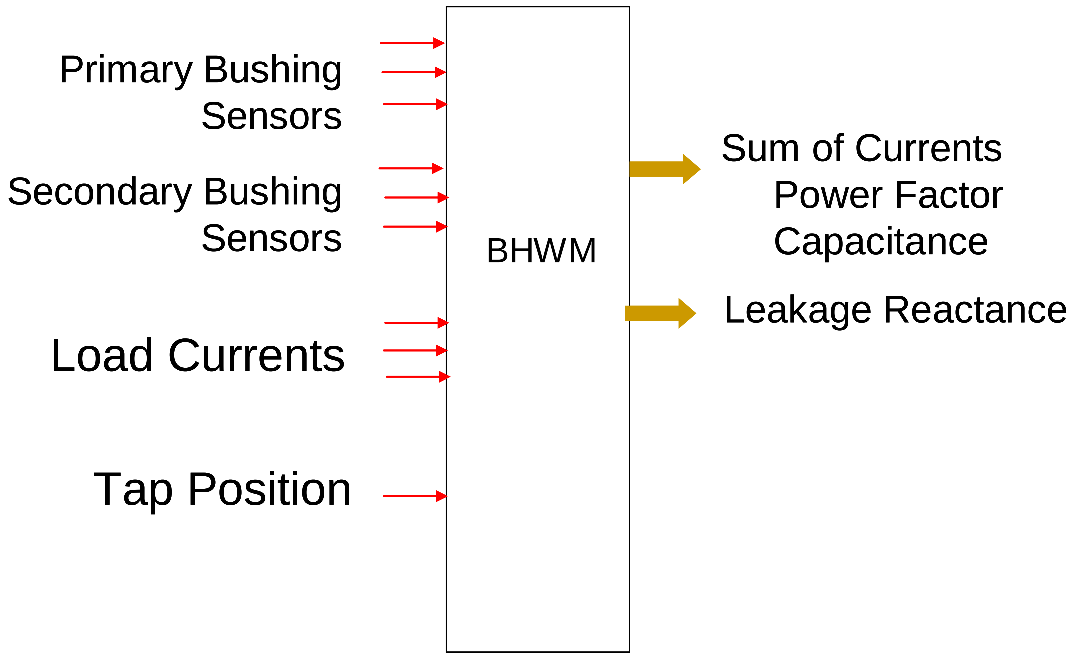
Winding Distortion

Transformers are designed to withstand high levels of mechanical stress caused by through faults. The stray magnetic flux will cause large forces within the winding. If there is reduced clamping pressure or the clamping pressure is not designed to withstand these forces, permanent winding deformation or winding collapse can occur.

Often this damage as this is not known and the transformer remains in service. Subsequent faults most likely will cause transformer failure. Many companies have started to use frequency response analysis measurements to determine condition of the winding.

With the addition of three phase currents, the bushing monitor module shown in Figure 2a has the ability to monitor winding distortion on-line by monitoring and calculating the stray reactance. The stray reactance is what determines the impedance of the transformer.

The bushing sensors provide both voltage and phase angle information. Direct measurement of the load current on the transformer using an auxiliary current transformer on the secondary CT winding will provide additional needed information as to the phase shift between the voltages and currents. This allows one to calculate the impedance of the system and compare to factory and/or nameplate values. Figure 9 shows a block diagram of the system. A change in impedance of 3 – 5% will indicate severe deformation.



Block Diagram of Bushing and Winding Health Monitor

Figure 9

Partial Discharge

Failures of any of the dielectrics inside of a transformer may be preceded by partial discharge (PD). An increase in PD activity or an increase in the rate of the increase should be cause of concern. Since partial discharge can deteriorate into complete breakdown, it is desirable to monitor this parameter on-line. PD sources most commonly encountered are related to moisture in the insulation, tracking on paper and barriers, cavities in solid insulation, metallic particles, and gas bubbles generated due to some fault condition.

Partial discharges in oil will produce hydrogen which is dissolved in the oil. However, the dissolved hydrogen may or may not be detected, depending on the location of the PD source and the time necessary for the oil to carry or transport the dissolved hydrogen to the location of the sensor.

Most transformers are tested of PD activity during normal factory acceptance tests. Typical levels of PD activity are shown in Table 1.

Table 1

Common PD levels

Category	PD level – Pico-Coulombs
Defect Free	10 – 100 pC
Normal deterioration	< 500 pC
Developing Defects (irreversible damage to paper)	1,000 – 3,000 pC
Breakdown of oil	10,000 – 100,000 pC

Both electrical and acoustic PD detection each have advantages and disadvantages and are complimentary rather than exclusive.

A partial discharge exhibits, besides other phenomena, a fast transient electrical pulse and an acoustic "bang". Depending of the location of the PD and the coupling path between the event and the detector, the electric or acoustic signal can be used to detect the PD. Both methods have different detection ways and sensitivities for unwanted signals (noise). The acoustic PD detection is most useful for events within the line-of-sight of the acoustic transducers. This limits the detection range, but also the amount of noise.

The electric PD detection covers a wider area, including e.g. bushing and tap changer. External noise will also be detected and is difficult to remove. The correlation between instrument reading and actual discharge magnitude is better than with the acoustic method. Several international standards exist that define the instrument response, which is the readout in pico-Coulomb or micro-Volt, allowing a better comparison between manufacturer and in-field measurements.

Table 2 provides a comparison of both methods.

Table 2

Comparison of Electrical and Acoustical PD detection on Transformers

Source	Electrical Detection	Acoustic Detection	Remarks
PD on the outside of the winding	Yes	Yes	Best use for acoustic detector, location
PD within the winding	Yes	Unlikely	Strong acoustic attenuation inside the winding.
PD between winding and core	Yes	Difficult	Acoustic signal reflection at the core required
Arcing / tracking of the oil surface	Yes	Yes	
Arcing / tracking of the bushing surface in the oil	Yes	Yes	
PD in the bushing	Yes	possible	Safety Concerns with Acoustic
PD in the de-energized tap changer	Yes	Yes	
PD in the on-load tap changer	Yes	Yes	

Electrical Method

The electrical signals from PD are in the form of a unipolar pulse with a rise time that can be as short as nanoseconds. The pulse rise time at the origin is dependent upon the type of discharge. Breakdown of an oil gap is a very fast process while a surface discharge may have up to ten times longer duration. PD pulses have a wide frequency content at the origin. The high frequencies are attenuated when the signal propagates through the equipment and the network and pulse shape is also modified due to multiple reflections and exciting resonant frequencies of elementary circuits. The detected signal frequency is dependent on the original signal, pulse propagation path to the sensing point and the measurement method.

Electrical PD detection methods are often hindered by electrical interference signals from surrounding equipment and the network. Most common and most difficult noise sources are aerial corona discharges and discharges to electrostatic shields that are not properly connected to either the HV bus or ground. Any on-line PD sensing method must have methods to minimize the influence of such signals.

The most common method for PD detection is to decouple the High Frequency partial discharge signals using sensors that are capacitivly coupled to the HV bus (coupling capacitor). Most HV apparatus have a natural “capacitor” built into the HV bushings or CTs have a convenient point for connection of the PD instrument. Bushing test tap or CT shield leads are frequently used for partial discharge measurements along with power frequency insulation tests.

The most popular method to interpret PD signals is to study their occurrence and amplitude as a function of the power phase position; this is called phase-resolved PD analysis (PRPDA). This method can provide valuable insight into the type of PD problem present.

The best method of noise rejection for in field measurements employs the use of multiple sensors. Use of a single sensor model in the field is unlikely to produce satisfactory results. If several sensors of different types or at different locations are employed, the possibilities to reduce external influences are greatly enhanced. Generally, the multi-sensor approach can be split into two processes: separate detection of external signals and energy flow measurements.

Energy-flow measurements use both an inductive and a capacitive sensor to measure current and voltage in the PD pulse. By the tuning of the signals from the two sensors, they may be reliably multiplied and the polarity of the resulting energy pulse determines whether the signal originated inside the apparatus or outside.

A modern PD instrument should employ both processes of the multi-sensor approach allowing the comparison of PD pulse magnitude from different sensors and pulses polarity for energy flow measurements.

Figure 10 – Acoustical sensors installed on transformer tank

Acoustic Methods

Acoustic emissions (AE) are transient elastic waves in the range of ultrasound, usually between 20 kHz and 1 MHz, generated by the rapid release of energy from a source. Partial discharges are pulse-like and cause mechanical stress waves (acoustic waves) to propagate within the transformer. If the stress waves propagate to the transformer tank wall, they may be detected with a transducer that is tuned to the right frequency.

PD sources can be located by measuring the relative time of arrival of acoustic waves at multiple transducer locations

In typical applications, the signals from a group of externally-mounted acoustic sensors are collected simultaneously and analyzed to detect and locate PD. However, as the acoustic signal propagates from the PD source to the sensor, it will generally encounter different materials. Therefore, acoustic signals can only be detected within a limited distance from the source. Consequently, the sensitivity for PD inside transformer windings, for example, may be quite low.

Though not disturbed by signals from the electric network, external and internal influences in the form of rain or wind and non-PD vibration sources like loose parts, cooling fans and oil flow from transformer oil circulating pumps will generate acoustic signals that interfere with the PD detection. These non-PD acoustic signals may extend up to the 50 to 100 kHz region. To diminish the effects of this disturbance, acoustic sensors with sensitivity in the 150 kHz range are usually employed. Such sensors may, however, have less sensitivity to PD signals than lower frequency sensors.

Figure 11 (a) shows an on-line continuous PD monitor that is available for use on motors, generators, switchgear, cables and transformers. It uses the same bushing sensors as the BHWM sown in Figure 2. An additional radio frequency current transformer mounted on the neutral bushing bus or cable or on the tank ground for noise cancellation purposes. Figure 11 (b) shows a complete monitoring system covering all aspects covered in this paper, which includes a power supply, Main CPU with communications and other I/O, Bushing and Winding Health Monitor (BHWM) and a 15 channel PD Module (PDM).

(a) Continuous PD Monitor with optional power supply and display

(b) Complete System diagnostic monitor for transformers

Figure 11

Summary

As technology advances, additional continuous or on-line monitoring techniques are being developed and proven the in the field. This paper presented some newer on-line diagnostics methods and provided examples and methods of monitoring and diagnostics for bushings and windings on transformers.

Biographies

Claude Kane has nearly 35 years of experience in the installation and preventive and predictive maintenance practices on a large variety of power distribution and generation equipment. He graduated from the Milwaukee School of Engineering in February 1973. He started with Westinghouse as a field service engineer and has held a number of technical and management positions. He has presented numerous technical papers on the subject of partial discharge at numerous IEEE conferences. He also was on the committee for the development of the IEEE Guidelines for the Measurement and Analysis of Partial Discharge on Rotating Equipment (P-1434). Claude is President of Electrical Diagnostic Innovations and is based in Minneapolis, MN.

Dr. Alexander Golubev received his MS in Experimental Physics and Ph.D. in Physics and Mathematics from the Moscow Physical Technical Institute (Russia) in 1978 and 1985, respectively. He has an extensive experience in research and design in Laser and Electron Beam Generation, Plasma Coatings, High Frequency Measurements. Since 1995 he is a Manager of R&D Engineering of the IPDD. Alexander is Chief Technical Officer of Electrical Diagnostic Innovations based in Minneapolis, MN. He develops new technologies for on-line monitoring and diagnostics of high voltage electrical equipment produces monitoring equipment and provides on-site expert evaluations of equipment condition for electric utilities and industrial customers.