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On-Line Condensing Bushing Monitoring System

This article shows the work principle of On-Line High-Voltage Condensing Bushing Monitoring in equipment as transformers and reactors, with examples of applications and the typical topology of one system. The advantage of system is avoid periodic disconnections for tests, substituting preventive maintenance for the maintenance based on state, with economy and reduction of the fails risk.

Marcos Eduardo Guerra Alves,
Treetech Sistemas Digitais

Bushings are accessories used in high-voltage equipment for the purpose of providing safe passage for electric current from the external environment to the interior of the equipment, as well as providing the necessary insulation in relation to the casing of the equipment. A few of the more common examples can be found on power transformers, reactor shunts and high-voltage circuit breakers.

Despite being accessory to the different equipment types mentioned, and in general being of much lower unit cost as compared to the overall cost of the equipment, bushings perform a function that is essential in operating the equipment.

On the other hand, bushings are subject to considerable dielectric strains, and a failure in their insulation may result, not only in damage to the bushing itself, but also to the entire equipment to which it is associated. In extreme cases, a dielectric failure in a bushing can result in total destruction of the high-voltage equipment (in power transformers, for instance, losses stemming from an event of this type can be worth a few hundred times the unit cost of the bushing that originally caused the problem).

Among the different existing types of bushings, the condensing bushing stands out in high and extra high-voltage applications. In these bushing the insulating body is made up of a staggered arrangement of several concentric cylindrical layers of insulating material and layers

The objective of the On-Line Condensing Bushing Monitoring System is the detention of alterations in the insulation still in its initial phase, indicating development of conditions that will be able to lead to the imperfection dielectric of equipment as transformers and reactors.

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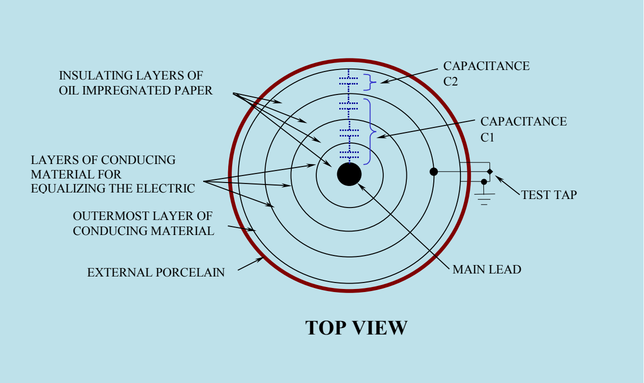

Illustration 1 – Construction details of a condensing bushing

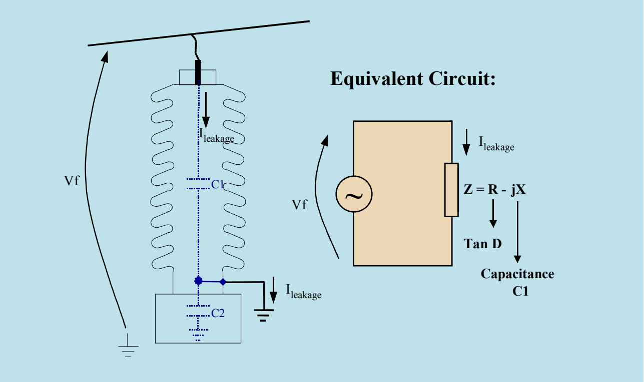

Illustration 2 – Equivalent circuit for an energized condensing bushing

of conducing materials for the purpose of making the electric field as uniform as possible. The innermost conducing layer may be connected to the main lead, in order to increase the radius and reduce the electric field in this region (also reducing the intense electric fields that may be caused by surface roughness on the main lead). The outermost conducing layer is connected to the flange of the bushing that, in its turn, is grounded. The intermediate conducing layers are insulated, with floating potential. For outdoor applications, the entire set must be placed inside a waterproof container, frequently made of porcelain. The connection of the last conducing layer (or of one of the outermost layers) to ground is usually performed by way of removable connection close to the base of the bushing, called voltage tap or test tap. (See illustration 1).

The set described in the previous paragraph acts electrically like several capacitors connected in a series array, forming a capacitive voltage splitter. In this way, the total potential differential for the main lead in relation to ground is shared equally among the different capacitors.

When the operating voltage is applied to a condensing bushing, a current known as the leakage current, begins circulating through the insulation, due mainly to their capacitance, and in much lower proportion due to the dielectric losses (expressed by the dissipation factor or delta tangent). Illustration 2 depicts this situation; in it we can see the electrical equivalent obtained with the construction shown in figure 1, with the bushing energized.

This electrical equivalent model is the "series" one. A "parallel" model could be used instead with the same results. With the model adopted we have the resulting leakage current:

$$I_{leakage} = \frac{Vf}{Z} = \frac{Vf}{R - jX}$$

Where:

"R" denotes the resistive component of insulation impedance which generates the resistive part of leakage current, associated with dielectric losses, being "X" the reactive component due to the insulation capacitance.

The objective of on-line monitoring of condensing bushings is detection of changes in the insulation of the bushing while still in the initial phase, pointing to the development of conditions that may lead to a dielectric failure in the equipment. To achieve this it is necessary to detect, with the bushing energized, changes in capacitance and in delta tangent values of the insulation, that is to say, changes in the "Z" impedance of the insulation of the bushing.

Methodology

In each bushing, the leakage current $I_{leakage}$ flows through capacitance *C1* to ground, passing through the test tap, with this current being a function of the phase-ground voltage and the impedance of the insulation. Thus, any change in the impedance of the insulation (capacitance or dissipation factor) will be reflected in a corresponding alteration in the value of the leakage current that, in theory, could be used in detecting the change that occurred in the impedance.

However, one of the obstacles found in detecting using the process described above is the order of magnitude of the changes that must be monitored. Changes so small as an algebraic increment of 0.3% in the dissipation factor of a bushing may represent the difference between a new bushing, in good conditions, and a borderline acceptable bushing. It is clear that such a slight change in the dissipation factor will cause a practically insignificant change in the leakage current of the bushing, making unfeasible detecting this only by way of monitoring each bushing's leakage current.

One of the techniques that allows the practical limitation shown to be overcome is using the vectorial sum of the leakage currents of the three bushings deployed in a three-phase system. In an arrangement of this sort, the three currents will have a phase difference in relation to each other of approximately 120º, and usually will be of the same order of magnitude once, in principle, the three bushings will have similar capacitances and the voltages of the three phases will be close to balanced. This way, the sum of the three leakage currents tends to a value quite a bit lower than for each of the leakage currents taken individually, as shown in illustration 3.(a) for a given initial condition of capacitances and dissipation factors.

Now, let's suppose that a change has occurred in the capacitance and in the dissipation factor of the bushing for phase A, as shown in illustration 3.(b), the Change Vector ΔI, that expresses de displacement of current I_a from its initial value to the final one, is also reflected in the sum current, which is altered

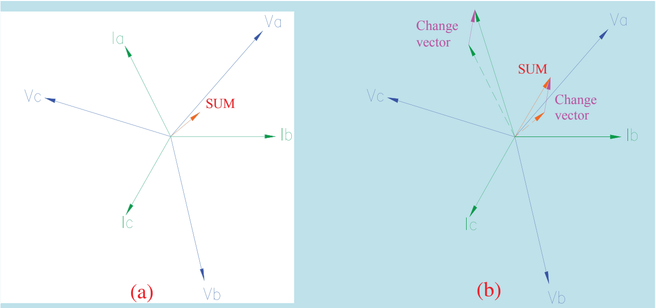

Illustration 3 – Leakage current in three bushings of a three-phase system and their vectorial sum; (a) for a given initial condition; (b) with alteration in the capacitance and dissipation factor of the bushing in phase A

in relation to its initial value according to the same Change Vector ΔI:

$$\Delta I = I_{a\ NEW} - I_{a\ OLD} = I_{SUM\ NEW} - I_{SUM\ OLD}$$

This Change Vector has a practically insignificant weight if compared to the magnitude of leakage current of phase A. However, the same does not happen when this vector is compared to the sum current, which allows its detection and, consequently, detection of the change that took place in the impedance of this bushing.

By the above stated, a few intrinsic characteristics of the method used can be perceived:

An initial reference set of currents must be defined for the system, so that subsequently these can be compared to the new readings obtained on-line, in order to determine the changes occurred in the bushing's capacitance and dissipation factor;

Absolute values for capacitance and delta tangent of bushings are not measured, rather what is measured instead are the variations that occur in these parameters. However, once the initial values for capacitance and delta tangent are known for each bushing (values found when the initial reference current set is defined), measuring the variations that take place allows the existing values for capacitance and delta tangent to be known;

For new bushings, the initial values can be defined as the rated values supplied by the manufacturer on the equipment plaque for capacitance and delta tangent. However, for bushings in operation, it is advisable that, while installing the on-line monitoring system, these parameters should be measured using conventional methods, with de-energized bushings. This ensures the monitoring system will use correct values for the initial reference set.

Another issue, that has not been dealt with so far, is that leakage currents and the sum current are not only influenced by changes in the capacitance and delta tangents of the bushings, but also by changes in the phase-ground voltage in each bushing. This influence is eliminated by way of mathematical and statistical treatments performed on the readings. This is also the reason for determining the initial reference set of currents during the 10 days following the beginning of operation of the monitoring system. Likewise and for the same reasons, the process of measuring the changes occurred has a time response to reach stabilization at the final value after a change in capacitance and tangent delta of approximately 10 days.

Security Precautions

As expounded in the above introduction, the bushing's physical construct creates a capacitive voltage divider, with its lower end normally being short-circuited grounding the tap of the bushing, so that the tap's voltage in relation to ground is zero volts. In order to be able to measure the leakage current for the bushing, this direct grounding is removed and replaced by the leakage current measurement circuit. Due to this circuit's low impedance, the tap's voltage in relation to ground remains close to zero. We should bear in mind the fact that, in case of accidental interruption of this circuit, the capacitive voltage divider will generate a voltage on the tap of the bushing that will normally display values higher that the tap's dielectric rigidity in relation to ground, risking damaging the bushing.

In order to avoid this event, the connection adaptor of the tap of the bushing has a voltage limiting device that becomes conducive in case the measuring circuit opens, thus supplying the leakage current with a low impedance path, so that the tap's voltage to ground remains on the order of a few volts. This limiter device is not subject to wear of mechanical or electrical natures, allowing it to carry the leakage current for indeterminate time.

Examples of applications

Illustrations 4 and 5 illustrate two facilities with bushing monitoring applied. The typical bushing monitoring topology used can be observed in these figures. The system is comprised of three basic components:

- a tap adaptador – provides electrical connection to tap for bushing, as well as weatherproofing it. The device features protection against accidental opening of the measuring circuit, preventing the tap from remaining open;
- measuring module – receives the leakage currents from three bushings in a three phase set, reads these currents and performs a first level of processing of the information, making them available to the interface module through a serial communication port; and
- interface module – receives information from measuring module(s) and performs mathematical and statistical processing, making available as result current values for capacitance and tangent delta on front panel displays. This module features analog outputs (mA), alarm contacts and serial communication ports.

Figure 4 shows bushing monitoring for transformer primary and secondary of two 230/138 kV, 150 MVA, three-phase transformers in operation in southern Brazil. The figure shows: a) tap adaptador in one of the bushings of the primary; b) tap adaptador in one of the bushings on the secondary; c) measuring modules for bushings of primary and secondary; and d) interface module.

Figure 5 shows bushing monitoring for primary and secondary of two

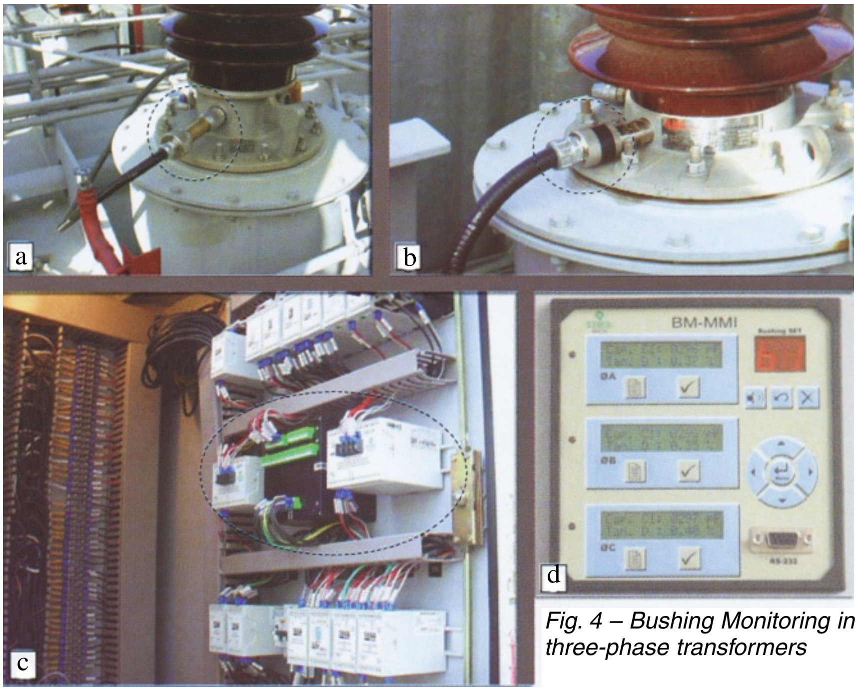

Fig. 4 – Bushing Monitoring in three-phase transformers

Fig. 5 – Bushing Monitoring in mono-phase transformers

525/230 kV, 1000 MVA, single-phase transformer banks in operation in San Diego, California,

USA, showing: a) tap adaptor in one of the bushings of the primary; b) tap adaptor in one of the bushings of the secondary; c) panel of the secondary; and d) interface module installed in the substation control room.

Conclusion

Condensive bushings are an essential accessory in the safe operation of a range of high-voltage equipment, such as power transformers and circuit breakers. This article has demonstrated the principle of operation that allows on-line monitoring of this type of bushing, as well as a few examples of typical monitoring system applications and their topologies. This brings about a reduction, or even eliminations, of periodic shut-downs for test on de-energized bushings, thus replacing preventive maintenance by status-based maintenance. In addition to the savings obtained from eliminating shut downs and maintenance procedures that most times prove to be unnecessary, on-line bushing monitoring reduces the risk of catastrophic failure that could occur in the time interval between preventive maintenance actions, which usually have a frequency of years. ●