The difference between safe and reliable on-line bushing monitoring and false alarms often lays in the quality of the sensor design and the installation procedure

ABSTRACT

On-line monitoring has proven to be an effective technology to detect deteriorating high voltage bushings and prevent failures. While there is much focus placed on the monitor and the data it provides, the sensors used to transmit the signals are often overlooked. An on-line bushing monitoring program is only as good as the quality and reliability of the sensors used to provide the signals. Many problems and false alarms can be avoided by using a properly designed sensor and making sure it is correctly installed. This article will discuss what to consider when selecting a bushing sensor and how to install the sensor properly.

KEYWORDS

open circuit protection, transient surge protection, moisture ingress, power factor

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Bushing sensors and their role in reliable on-line bushing monitorings

1. Introduction

Although bushing manufacturers continue to improve the quality and reliability of their product, the 2015 CIGRE Transformer Reliability Study shows that bushing failures continue to be one of the leading causes of transformer failures around the globe. The study also shows that bushing failures were the cause of over one third of the transformer failures involving fires or explosions. Due to the financial impact a catastrophic transformer failure can have, many utilities are turning to on-line bushing monitoring to identify deteriorated bushings earlier and prevent transformer failures [1].

On-line bushing monitoring systems have been successfully used by the utility industry for over 20 years. They have a proven track record for being able to identify degrading bushings early in the failure process. By providing early warning, users have additional time to plan and schedule an outage to replace the bushings. While there are many users that have successful on-line bushing monitoring programs, some users cite problems with false alarms from the monitor. While there can be multiple reasons for a false alarm, sensor related problems are one of the more common complaints. The use of properly designed sensors and correctly installing the sensors can improve the reliability of the on-line monitoring system.

This article will discuss the different styles of bushing sensors available on the market today, the protection the sensors must provide to prevent equipment damage and protect utility personnel, and the installation procedures that can help to prevent false alarms.

2. Sensor design

IEEE Standard C57.19.100, IEEE Guide for Application of Power Apparatus Bushings offers the following guidance when selecting a bushing monitoring system/sensor: "Bushing monitors are installed on bushing cap taps to allow for on-line testing and monitoring. These [devices] allow for continuous monitoring or periodic testing of bushings without removing the bushing from service. Since the monitors replace the existing cap tap cover, the user should insure proper fit of the monitor to prevent moisture ingress into the cap tap. A voltage is then brought from the monitor to an accessible area of the transformer to perform the monitoring. The user should consult with the manufacturer of the monitor to determine the voltage levels that are normally expected and the maximums that could be reached should the device fail. Operational guide-

When installing a bushing monitor, maintaining the ground connection is of utmost importance

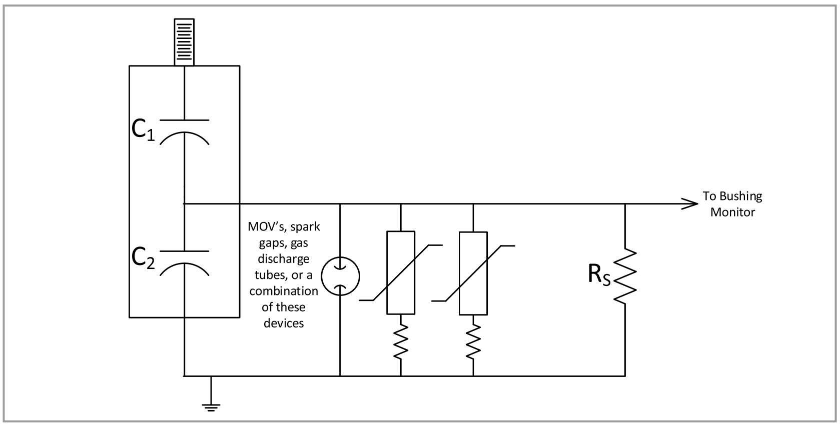

Figure 1. Resistive style bushing sensor

The sensor must provide redundant overvoltage and overcurrent surge protection from damaging the bushing and monitoring system

lines can then be developed by the user to determine the level of safety requirements and experience of personnel who should have access to the devices." [2]

3. Sensor types

3.1 Resistive

Resistive style sensors, Fig. 1, utilize resistors connected between the bushing tap and ground as the primary method to limit the voltage from the test tap. Should the resistors fail, metal oxide varistors (MOVs) or similar overvoltage protective devices, limit the voltage output from the tap to acceptable levels. Current limiting resistors in series with the MOVs can help to prevent MOV failures. Since the test tap of the bushing is solidly grounded through resistors, this type of sensor closely matches the original bushing design where the C_2 capacitance is grounded when in service through the tap cover. To protect against overcurrent, gas discharge tubes or similar surge protection devices are used. The resistor (R_S) is used to limit the test tap voltage. The resistor(s) may be located in the bushing monitor or in the bushing sensor. Locating the resistor(s) in the bushing monitor allows for standardization of the bushing sensor design. Since the sensor design is not dependent on the size of the resistor required, the same sensor can be used for almost all system voltages and bushing C_1 capacitance values; the exception being extra high voltage systems (EHV) where additional protection elements are often required [2, 3, 4, 5].

3.2 Capacitive

Capacitive style sensors, Fig. 2, utilize a capacitor, C_S, in parallel with the C_2 capacitance of the bushing. The sensor capacitor (C_S) forms a voltage divider with the C_1 capacitance of the bushing. The capacitor is sized to limit the voltage present in the tap. If the capacitor C_S is located in the sensor body, the size of the capacitor must be considered in addition to the type of test tap adapter when ordering the bushing sensor. Should the capacitor C_S fail, MOVs or similar overvoltage protection is provided to limit the voltage level to acceptable levels [2, 4, 6].

Some capacitive style sensor manufacturers rely on active electronic circuits to provide an alternative ground path should the voltage in the tap rise to unacceptable levels. The use of passive electronic components is generally recommended due to their high reliability and the simplicity of the design.

3.3 MOV

MOV style sensors, Fig. 3, rely solely on arrestors to limit the voltage level from the tap to acceptable levels. Since this type of sensor provides only one layer of protection, it is not commonly found today.

4. Sensor protection

4.1 Open circuit protection

The ANSI type test taps used on bushings require the tap to always be grounded during operation. The loss of the ground connection will result in high voltage at the tap. To prevent generating high voltage, the tap cover grounds the test tap to the flange of the bushing. When installing a bushing monitor, it is extremely important that the monitor maintain this ground connection. Without proper protection, failure to maintain this ground connection will result in high voltage not only at the test tap, but also in the transformer cabinet and at the monitoring equipment. The maximum voltage present in an ungrounded test tap is dependent on the ratio of the C_1/C_2 capacitances of the bushing (cable capacitance and system burden effects are assumed to be minimal) as shown in equation (1). Let us consider a high voltage bushing applied on a 500 kV system with a C_1 capacitance of 300 pF and a C_2 capacitance of 3000 pF:

$$\textit{Open circuit voltage} = V_{OC} = V_{\text{Ø-G}} \frac{C_1}{(C_1+C_2)} = \frac{500\ \text{kV}}{\sqrt{3}} \cdot \frac{300}{(300+3000)} = 26.2\ \text{kV} \qquad (1)$$

In the worst case for a bushing where $C_1 = C_2$, an ungrounded test tap could float to ½ the line to ground voltage of the system. To prevent high voltage at the tap and to prevent overstressing the C_1 insulation system of the bushing, the sensors connected to the test tap must:

- have open circuit protection to protect operating personnel from electric shock and to maintain a safe operating voltage at the monitor;
- protect the bushing insulation system and the test tap from overvoltage in case of an open circuit between the sensor and the monitor; and
- provide a reliable current output with minimal phase shift from the test tap for the monitoring system.

All bushing monitor manufacturers provide some form of open circuit protection in their sensors. However, the maximum voltage output under open circuit conditions will vary. At a minimum, the bushing sensor should limit the open circuit voltages to the lower of the manufacturers specified test tap voltage or to a low voltage (50-300 VAC) as defined by OSHA 1910.303. Voltages in this range are commonly found in transformer control cabinets and hence will allow electrical personnel to follow their general safe work practice of avoiding contact with the electrical parts operating at this voltage when working in the cabinet. Maintaining an extra low voltage (<50 VAC) during an open circuit can further reduce the hazards to utility personnel.

If subject to long duration overvoltage conditions which exceed the design specifications, overvoltage protective devices can fail. Current limiting resistors can help to prevent the failure of MOVs. Back up protection or redundant overvoltage protection devices are recommended since the sensors must maintain a ground connection at the test tap to prevent hazardous overvoltage from occurring. While maintaining this ground connection is necessary for all bushing types, manufacturers may not recommend on-line bushing monitoring due to the concern that the sensor may not maintain this ground connection. However, a properly designed sensor that utilizes redundant protective devices and failsafe protection can minimize these concerns [2, 3, 7, 8, 9].

4.2 Transient surge protection

In addition to overvoltage protection, the bushing sensor should also provide overcurrent protection against lightning and switching surges. The overcurrent protection required is dependent on the rate of voltage rise. Using the standard 1.2/50 µsec pulse, commonly specified for surge withstand protection, would result in a surge current of 125 amps for an indirect 500 kV lightning strike as shown in equation (2).

$$I = C_1 \frac{dV}{dt} = 300 \cdot 10^{-12} \cdot \frac{500{,}000}{1.2 \cdot 10^{-6}} = 125 \text{ amps} \qquad (2)$$

Designing for surges with a shorter rise time than the typical 1.2x50 µsec waveform will result in a more robust sensor design and help to eliminate premature sensor failures. The same 500 kV lightning strike with a 0.1 µsec rise time would result in 1500 amps of surge current.

IEEE 62.41 recommends that surge suppressors (applicable for sensing circuits) be designed for lightning stroke currents of at least 10 kA. Using a larger stroke current capability will increase the life expectancy of the surge protective devices (SPD).

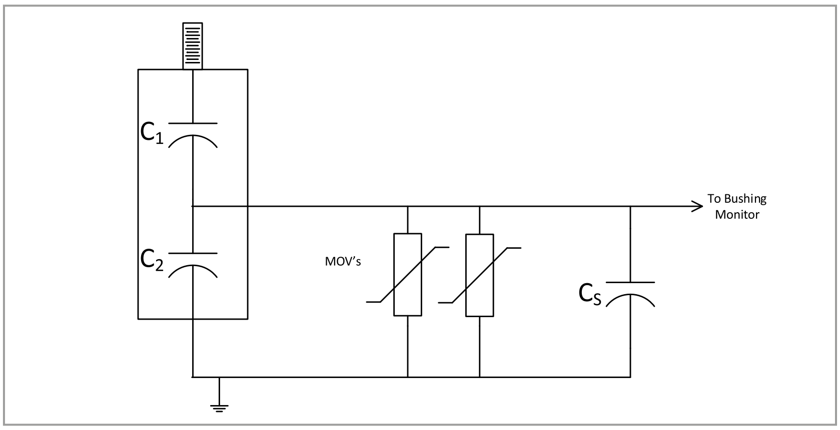

Figure 2. Capacitive style bushing sensor

The use of passive electronic components for protection is recommended due to their high reliability and simple design

Lightning related surges will have higher voltage with a shorter duration rise time, while switching related surges will have lower voltages and longer duration. Both need to be considered when designing the transient surge protection of the sensor. While the maximum expected current surge is only a few thousand amps, higher levels of protection are achievable and should be considered [7, 8, 9].

IEEE C37.90.1 and IEC 60255-26 provide guidance on transients and other electrical disturbances that are commonly found in high voltage substations. The standards define the surge withstand capabilities that are required for relays and relay systems. While these standards do not apply directly to bushing monitors and sensors, the fast transient and oscillatory waveform tests described in these standards are typical of the disturbances that bushing monitoring systems are exposed to [10, 11, 12]. Hence, bushing monitor manufacturers should design their equipment to meet the surge withstand capabilities specified in these standards.

5. Sensor installation

Moisture ingress through to the test tap has always been a concern with high voltage bushings. Changes in C_2 power factor due to moisture ingress is often listed as one of the leading reasons why utilities replace bushings on transformers. With

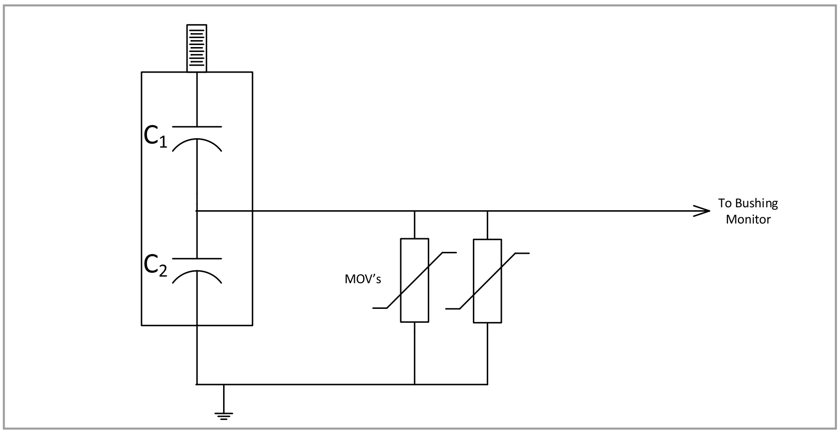

Figure 3. MOV style bushing sensor

Figure 4. Bushing test tap with moisture ingress due to an improper sealing gasket

Since the sensor replaces the existing test tap cover, the user should insure proper fit of the sensor to prevent moisture ingress into the test tap

an on-line monitor, moisture problems in the test tap can impact the magnitude and phase angle of the leakage current making it appear that the problem is in the bushing C_1 insulation. Preventing moisture ingress, like that shown in Figure 4, requires the following elements:

1. A properly designed cover or sensor that fits snug and firm to the test tap
2. A conductive thread lubricant to prevent damage to the thread during installation
3. A properly sized O-ring or similar gasket material which allows for the correct seal and gasket crush
4. A compatible O-ring lubricant to improve the seal and prevent damage to the gasket during installation
5. Filling the test tap with oil or a dielectric grease to provide additional protection from moisture ingress

Most bushing manufacturers recommend filling the test tap with oil or a dielectric grease to help prevent moisture ingress. Hence, the sensor design must be compatible with mineral oil and capable of being operated with a wet or dry test tap. Following these simple and effective means of preventing moisture ingress can lead to years of trouble-free operation [3, 5].

Improper installation can have a significant impact on the readings from the bushing monitor and trigger false alarms. Figure 5 shows data from an online bushing monitor before and after repair of moisture ingress/contamination in the test tap of the X2 bushing. The figure shows the change in the phase angle of the X2 bushing leakage current compared to the reference bushing X1. Under ideal conditions, a 120-degree phase angle would be expected. If the system voltages are stable, an increase in the angle indicates an increase in the power factor of the X2 bushing. In this example, the phase angle of the bushing leakage current often exceeded 124 degrees and at times exceeded 125 degrees. Had this been an actual problem in the C_1 insulation of the bushing, this would have been equivalent to an increase in the C_1 power factor of the bushing from 0.35 % to over 7 %. The problem resulted in frequent alarms from the bushing monitor whenever the imbalance

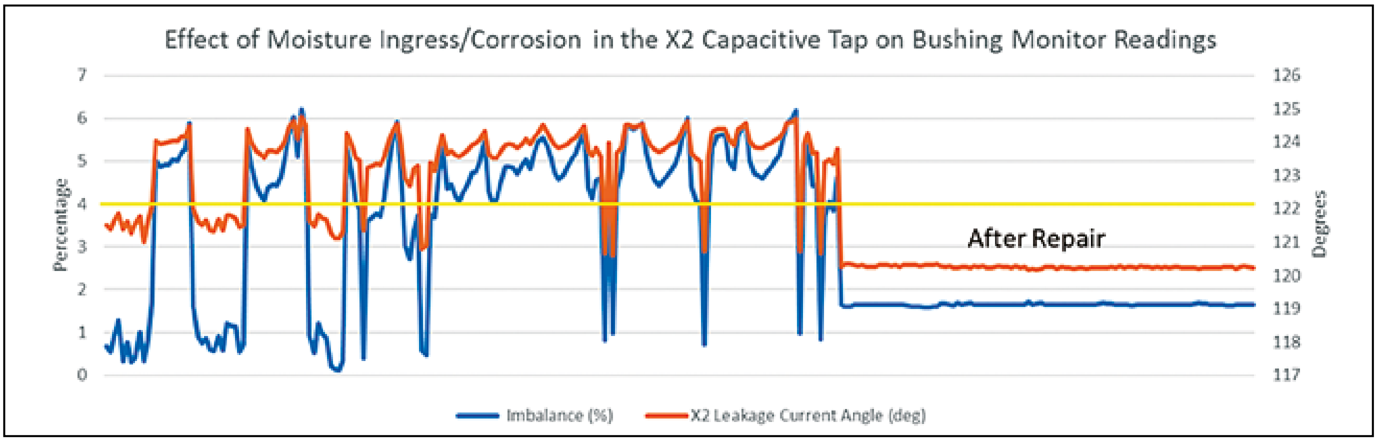

Figure 5. Data from a bushing monitor before and after repair of corrosion due to moisture ingress

Improper installation can have a significant impact on the readings from the bushing monitor and trigger false alarms

current exceeded 4 %. The utility downloaded the data from the monitor and noticed the erratic signals in the X2 bushing leakage current. After discussing the problem with the monitor manufacturer, a physical inspection of the test tap was performed.

Figure 6 shows the corrosion in the test tap and on the spring connection due to improper installation. The contractor failed to follow the instructions for the bushing and monitor during the installation. The moisture and corrosion in the test tap had a significant impact on the power factor readings of the X2 bushing and resulted in alarms from the monitor.

Conclusion

On-line bushing monitoring can be an effective tool to help utilities prevent transformer and bushing failures, and better manage their aging infrastructure. To be successful in the use of on-line bushing monitoring, the design of the bushing sensors and the installation procedures should not be overlooked.

The sensor must provide redundant open circuit (overvoltage) and transient (overcurrent) surge protective elements to protect the bushing and monitoring system from damage. The level of overvoltage protection, along with the design of the circuit, should be considered. Overvoltage protection which uses current limiting resistors in series with the protective device(s) can help to ensure long term safe and reliable operation. Overcurrent protection of at least 10 kA per IEEE 62.41 should be provided. Bushing monitoring systems should be designed to meet the surge withstand capabilities per C37.91.1 and IEC 60255-26. Most bushings require that the test tap remain grounded when in service. Since these circuits also protect utility personnel from hazardous overvoltage conditions being present in the transformer cabinet, the reliability of these circuits is of utmost importance. Due to the critical nature of this protection, sensors that offer failsafe protection, in addition to overvoltage and overcurrent protection are recommended. The failsafe protection, as the name implies, will short the test tap to ground at the test tap should the primary protection fail.

Proper installation procedures are also required to prevent false alarms. Installation procedures should consider the fit of the sensor adapter to the test tap; the size and type of gasket material used; the lubrication of the gasket(s); and filling the test tap with mineral oil or a dielectric grease to prevent moisture ingress.

Figure 6. Corrosion found in the test tap after removing the transformer from service

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