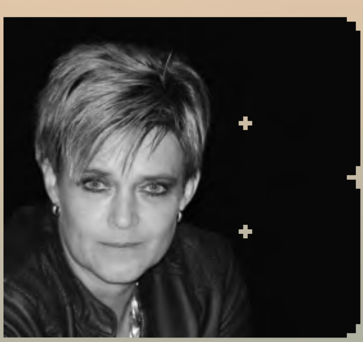
Transformer Bushings:

Breakdown Mechanism and the Appropriate Life-cycle Maintenance Implementation



Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that is part of the transformer system coupled with technical insight helps customers optimize their reliability maintenance and electrical asset lifetime.

Bushings cause 17% of all power transformer failures and are the third most common reason for transformer breakdowns.

Introduction

According to studies, bushings cause 17% of all power transformer failures and are the third most common reason for transformer breakdowns. High-voltage bushings contribute 30% to all fires and explosions associated with power transformer breakdowns. Effective diagnostic tools are therefore of the utmost importance and should be an integral part of the life-cycle oriented preventative maintenance strategy.

In this article, we will discuss the Dielectric Frequency Response (DFR) measurements as a supporting diagnostic tool for bushing condition assessment. The DFR method has proven to be very valuable to diagnose the bushing condition, plus has identified potential insulation system damage before a breakdown in various cases.

It is important to gain insight and understanding of the process of aging and the condition of the bushing.

Photo: Shutterstock

Life-cycle Orientated Diagnostics and Monitoring

Available Bushing Technologies

Four main categories were developed over the years for condenser bushings.

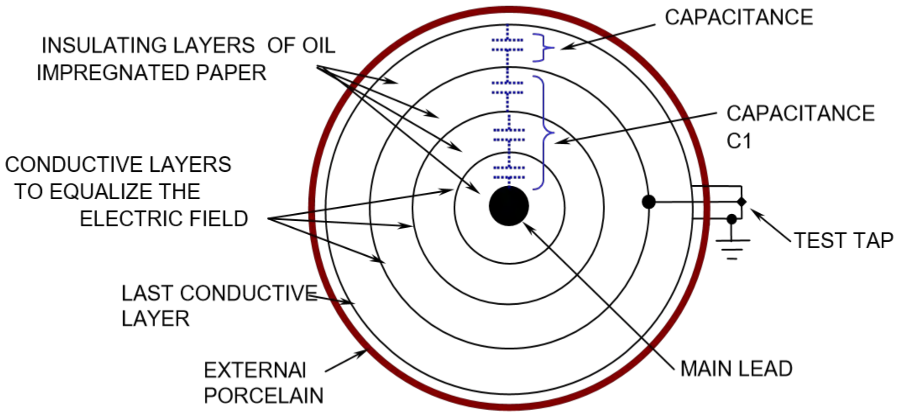
One of the first technologies was **Resin Bonded Paper (RBP)** used for more than 100 years. The production process causes partial discharge to occur in the bushings and therefore shows high DDF values. This technology has been mostly phased out due to technical reasons.

Second is **Oil Impregnated Paper (OIP)** technology, which is still used in about 60% of the market today. The condenser core is impregnated with transformer grade mineral oil and placed inside an insulating envelope built up from porcelain or composite material to seal the bushing against moisture ingress. These bushings can be manufactured at high quality with low capacitance losses and they can be free from partial discharges. The condenser core that is in a liquid environment may cause some leakage problems around the gaskets when the design is not properly done. If an internal electrical breakdown takes place (which is very rare) a high internal pressure can build up which can result in explosions of the bushings. Resulting from the explosion an arc usually originates, and this can result in a fire.

The **Resin Impregnated Paper (RIP)** technology is state of the art and consist of a wound core made of untreated crepe paper, which is then impregnated with a curable epoxy resin. For outdoor use, either porcelain or composite insulators are used. These bushings provide significant technical advantages such as being fully dry and pressure-free, feature a high-temperature class, normally stable and low partial discharge levels, low dielectric losses, fire-resistant, and outstanding mechanical properties. They tend to show higher procurement cost levels compared to OIP. They have lower life-cycle costs with reduced maintenance and monitoring efforts over the expected lifetime. These bushings are prone to moisture ingress into the paper layers of the insulation material if not stored or handled in the appropriate manner. This result in an increased loss factor which can cause a bushing to become unsuitable for operation.

Resin Impregnated Synthetics (RIS) technology where the hygroscopic paper has been replaced with non-hygroscopic synthetic materials. They are characterized by very low dielectric loss factor (tan delta), lowest possible partial discharge levels due to both the void free impregnation process and the electrical design. These bushings are almost immune to moisture ingress and therefore does not require special precautionary measures while being stored. These are expected to have the lowest lifecycle cost of all the bushings.

Figure 1. Constructive details of a condenser bushing



Close to 50% of serious transformer fires are initiated by Oil Impregnated Paper bushings and they are the most common cause of transformer fires.

The typical life expectation of any bushing type can be reduced by the following factors: excessive stress, voltage oscillations imposed by lightning strikes, frequent shunt reactor switching, and continuous high levels of harmonics.

One of the key factors in the successful management of bushings is to firstly avoid, but also detect PD activities to avoid breakdown.

Figure 2.
Bushings cause 17% of all power transformer failures and are the third most common reason for breakdowns [1].

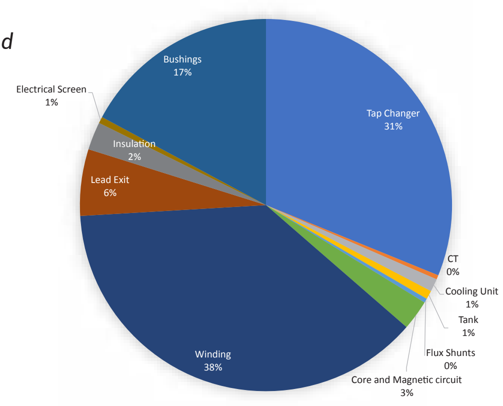
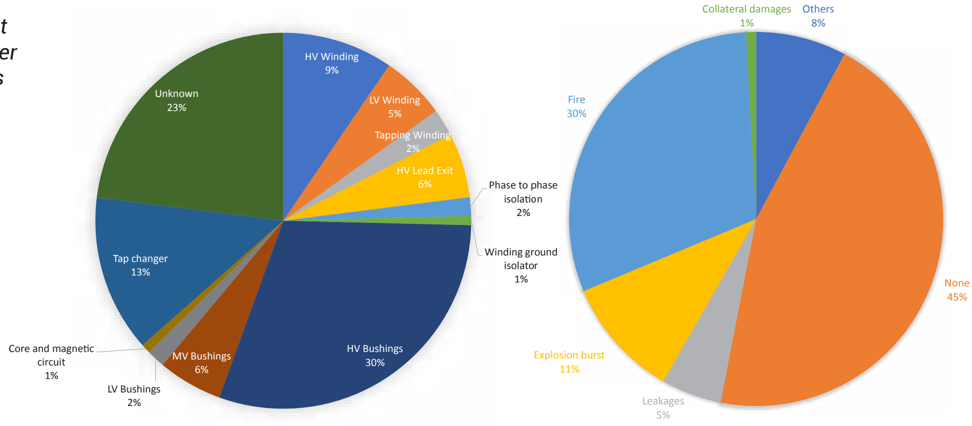


Figure 3.
Bushing failures are the most common cause of transformer fires and explosions: Failures with fire and explosion (left); Bushing failures (right) [1].



Bushings as the Main Contributors to Transformer Failures

Close to 50% of serious transformer fires are initiated by oil impregnated paper bushings and they are the most common cause of transformer fires.

Breakdown Mechanism of Transformer Bushings

The typical life expectation of any bushing type can be reduced by the following factors: excessive stress, voltage oscillations imposed by lightning strikes, frequent shunt reactor switching, and continuous high levels of harmonics. This may trigger premature breakdown of the bushings.

The characteristics of a distribution system may change due to expansion or a greater harmonic load due to installation on new equipment. A bushing breakdown can occur even when a transformer is operated within its maximum specified limits. This happens if the deterioration of the bushing's internal insulation system was not detected in time to act. All bushings will lose their electrical stress withstand capability over time – some quicker, other slower.

Over time the failure risk will increase because the capability to withstand stress will decrease as the equipment ages.

Often, the deterioration process of the bushing will start with Partial Discharge (PD), which initiates 'treeing' – small cracks. The discharge channels resulting from the treeing will carbonize further and the PD activity will increase up to a point where the inner foils of the field grading condenser core are being short-circuited. This will result in an increase of the electrical field stress on the remaining inner foils of the condenser core, and an interval flashover will finally occur and destroy the bushing.

One of the key factors in the successful management of bushings is to firstly avoid, but also detect PD activities to avoid breakdown. PD activity usually originates from excessive mechanical or electrical stress as well as the thermal ageing of the insulation material. Low quality bushings may show PD activity from the start. Bushings displaying PD activity at normal operating voltages should be avoided as they greatly increase the risk of premature failure. It is vitally important to determine the reliability of the infrastructure on a regular basis, and especially before exposing it to increased electrical stress. One way to reduce electrical stress would be by installing appropriate surge arrestors or by improving the grounding system.

Identifying the true state of the bushings is of the utmost importance to ensure a reliable network.

The tan δ measurement is a very strong tool to diagnose the bushing condition with respect to moisture ingress and the insulation deterioration resulting from this.

Establishing Diagnostic Methods to Determine Status of the Bushing's Insulation System

a) Measurement of the Dielectric Dissipation Factor Tan δ

An increased dielectric dissipation factor (DDF) leads to higher dielectric losses within the bushings. The temperature of the bushing will increase with higher dielectric losses and this will then increase the Dielectric Dissipation Factor again – creating a continuous cycle of degradation. A bushing of good design in good condition will have a capped temperature rise and the temperature rise will stop at an acceptable value without causing damage.

Frequently, when a bushing is in a bad condition – often due to moisture ingress over time – the positive feedback mechanism may not be stable anymore and the temperature will increase beyond the thermal stability limit. Now the busing will experience dielectric breakdown within the condenser core. Higher rated voltage bushings are generally more prone to this phenomenon.

Typical causes for an increased DDF (tan δ) over time include:

- Moisture ingress due to leakage
- Moisture ingress originating from the transformer oil
- Moisture ingress due to improper storage
- Ageing of paper (OIP, RBP and RIP technology) [1]

The tan δ measurement is a very strong tool to diagnose the bushing condition with respect to moisture ingress and the insulation deterioration resulting from this.

The DDF measurement should be done at high temperatures, close to the maximum permitted temperature for that specific type of insulation material, to ensure thermal stability of the bushing under demanding operational conditions and to identify possible moisture ingress. The practical application of this is sometimes not possible after the bushing has been installed in a transformer, here the DFR – dielectric frequency test has demonstrated that this method can deliver similar useful results at ambient temperatures, provided the relevant material specific technical data and properties from the bushing OEM is available and correctly incorporated. This might not be as easy, as only a few bushing manufacturers have these data available.

The DDF (tan δ) should be measured over a broader voltage range from about 2 kV to 12 kV. If the loss factor is not constant with an increasing voltage, this will typically indicate problems in high voltage or ground foil conditions.

b) Capacitance C Measurement

If the capacitance value increases, this is usually an indication of the partial breakdown on the inside of the condenser core. Due to this the field stress inside the bushing will increase and will lead to eventual breakdown of the condenser core of the bushing. Causes for this inner breakdown include:

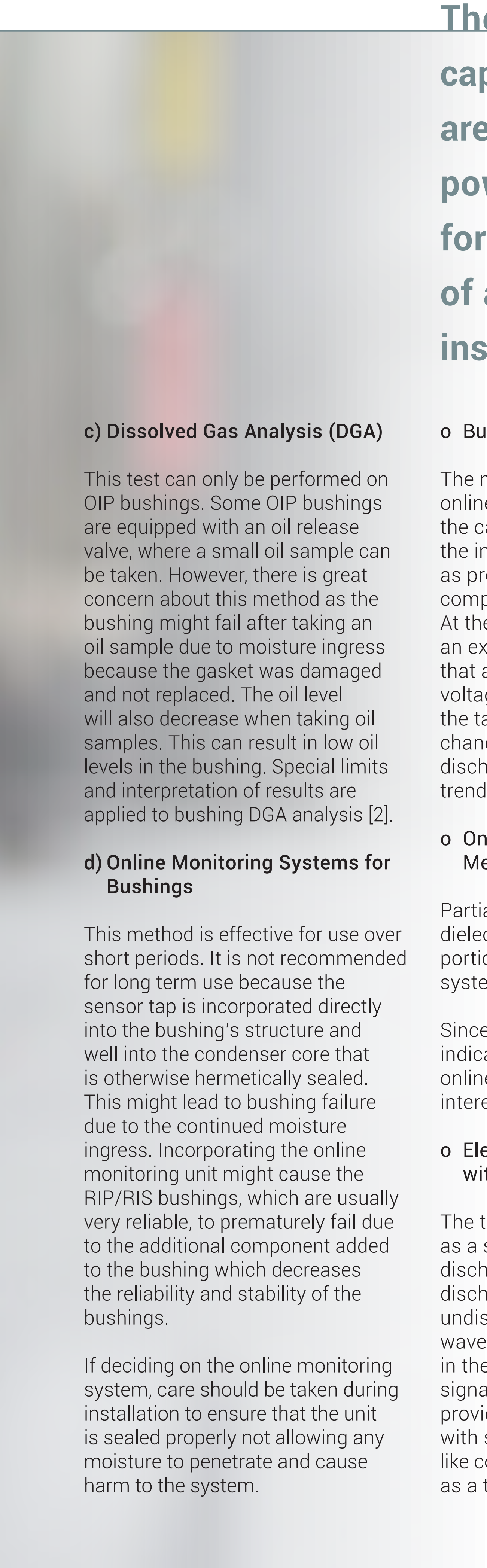
- Over voltages – lightning strikes, reactor switching operations, harmonics
- Continuous PD activity
- Contamination and bubbles remaining from the production process
- Deterioration of the insulating material

The DDF and the Capacitance C measurement are probably the most powerful diagnostic tools for assessing the condition of a bushing that has been installed on a transformer.
The most important factors for optimized lifecycle-oriented condition assessment of Capacitance and tan δ can be summarized as follows:

- Direct after installation an initial 'fingerprint' measurement should be done at a defined and recorded temperature – if possible – at different frequencies (DFR measurements) to ensure meaningful future diagnostics.
- The measuring of C and tan δ are performed at relatively low measuring currents and voltages, therefore other sources of electromagnetic interference can significantly impact the measurement results and cannot be avoided in most cases. These interferences are caused by circulating currents in grounding systems and radio interference and other sources. Ensure to document the setup for the initial measurement very accurately and repeat the follow up measurements under the same circumstances, if possible, with the same test equipment to achieve comparable meaningful results.
- Ensure identical temperature as during initial measurement: the condenser core temperature can take up to 48 hours to stabilize, which needs to be considered when performing follow up testing. If this is not possible, an OEM for interpretation of results is recommended as they might have the model and tools necessary for the correction of temperature measurement.
- Because increased DDF and C_1/C_2 may indicate increased moisture content with high probability, the lack of increase cannot guarantee the condition of the bushing insulation material to be acceptable. Therefore, the use of the DFR test method is recommended.

Photo: Shutterstock

Photo: Shutterstock



> **The DDF and the capacitance C measurement are probably the most powerful diagnostic tools for assessing the condition of a bushing that has been installed on a transformer.**

c) Dissolved Gas Analysis (DGA)

This test can only be performed on OIP bushings. Some OIP bushings are equipped with an oil release valve, where a small oil sample can be taken. However, there is great concern about this method as the bushing might fail after taking an oil sample due to moisture ingress because the gasket was damaged and not replaced. The oil level will also decrease when taking oil samples. This can result in low oil levels in the bushing. Special limits and interpretation of results are applied to bushing DGA analysis [2].

d) Online Monitoring Systems for Bushings

This method is effective for use over short periods. It is not recommended for long term use because the sensor tap is incorporated directly into the bushing's structure and well into the condenser core that is otherwise hermetically sealed. This might lead to bushing failure due to the continued moisture ingress. Incorporating the online monitoring unit might cause the RIP/RIS bushings, which are usually very reliable, to prematurely fail due to the additional component added to the bushing which decreases the reliability and stability of the bushings.

If deciding on the online monitoring system, care should be taken during installation to ensure that the unit is sealed properly not allowing any moisture to penetrate and cause harm to the system.

o Bushing Sensors

The mechanical installation of an online bushing sensor replaces the cap's function of rounding the insulation layers as well as protecting the taps internal components from contaminants. At the same time, the sensor creates an excellent electrical connection that allows the measurement of voltage and/or current present at the tap. With these measurements, changes in capacitance and partial discharge can be determined and trended.

o Online Partial Discharge Measurement

Partial Discharge (PD) is a localized dielectric breakdown of a small portion of a solid electrical insulation system.

Since partial discharges are early indicators of incipient faults, their online observation is of prominent interest.

o Electromagnetic Measurements with UHF Sensors

The transformer tank functions as a shield against external partial discharge, thus internal partial discharges can be detected relatively undisturbed by the electromagnetic waves. The combination of signals in the UHF range with electrical signals from the bushing tap provides a high sensitivity together with suppression of external noise like corona. The UHF signal serves as a trigger or gating signal for the electrical signals. The individual PD patterns do not allow for a pattern classification. After their combination, where the UHF signals serve as gating signals, a PD pattern can be recognized. The UHF signals that correspond to the partial discharge are transmitted to a display or measuring device. Online monitoring algorithms are used to decode the signals. The monitoring algorithm tells the users when there is any damage in the bushings of the transformers by measuring and sensing the partial discharge.

o Online Capacitance Measurement

Partial breakdowns between field grading layers result in an increase of capacitance. This change in the capacitance can be measured by electrical sensors.

o Sensing Capacitance Change

An electric sensor can indicate the change in the capacitance. When the sensor senses a change in capacitance in the bushing setup, the voltage signal corresponding to the change in capacitance is given by the sensor. These voltage signals are then transmitted to a display or a measuring device. They are decoded and evaluated using various online monitoring algorithms. This will be shown to the users by the intelligent system and the problem can be easily cleared without any major damage. Thus, the damage in the transformer bushings is measured and sensed by the change in the capacitance using this algorithm.

Some utilities have already started to apply regular DFR testing on their bushings, but the lack of knowledge to interpret the deviations over time from the original test causes a void in the application value of this test.

Table 1.
Useful diagnostic methods for transformer bushings

	tan δ	Capacitance	DGA	Partial discharge	Visual inspection	Thermal survey	DFR (C & tan δ)
On site, transformer not energized	X	X	X (if appl.)	-	X	-	X
On site, transformer energized	(X)*	(X)*	-	(X)*	X	X	-
High voltage test lab	X	X	X (if appl.)	X	X	-	(X)

**Only possible with appropriate on-line measurement equipment*

e) Partial Discharges

Partial discharges will lead to the degradation of electrical insulation material. This phenomenon occurs when there are defects in the electrical insulation like voids, cracks, and delamination. PD measurements are very difficult to perform on bushings that are installed on transformers. Online PD measurements may pick up on bushing issues that show high PD activity, but still, this will increase the risk of premature failure [3].

f) Visual Inspection

When assessments on bushings are done, a visual inspection is suggested. Any oil leaks, low oil level, damage to insulator should be noted and the impact assessed.

g) Thermal Survey

A handheld infrared scanner can be used to perform a unit baseload temperature measurement. This can be useful to detect hot joints, high stress areas and possible electrical breakdown.

Summary of Diagnostic Systems for Bushings

Four main categories were developed Follow-up measurements should be performed at time intervals recommended for the specific bushing type, the age of the bushing and the impact on the system if failure occurs. If the bushing was exposed to severe stress, it might require more attention to ensure that the internal insulation system has not suffered in any way.

DFR Measurements to Determine the Status of the Bushing's Insulation System

The Dielectric Frequency Response is done over a broader frequency range. This test is conducted when it is suspected that the bushings might have been damaged by exposure to excessive stress. The internal insulation system needs to be checked for damage to ensure that factory tested electrical insulation capabilities was not unduly compromised. If the withstand capability to grid disturbances is compromised, the overall reliability of the transformer unit is compromised. This test is also more accurate to determine moisture levels.

Some utilities have already started to apply regular DFR testing on their bushings, but the lack of knowledge to interpret the deviations over time from the original test causes a void in the application value of this test. If the measurements and deviations can be pinpointed to identify problem areas and show the degradation in the system, this can be a very valuable tool in the diagnostic chain [4].

Difficulties Experienced with DFR Measurements

Because of the frequency range for these tests, DFR measurements require a much longer measurement time. The additional testing hours increase the total working hours allocated to the field maintenance crew. Limited guidelines and models were developed to decrease the test time and to interpret the results of measurement. Operational asset performance leaders are currently developing guidelines in predicting remaining in-service life of an ageing bushing fleet.

Photo: Shutterstock

References

[1] Th. Schuette, E. Santos, Understanding the Breakdown Mechanism of Bushings and Implementing Appropriate Life-cycle Orientated Maintenance Strategies

[2] IEC 61464-1998, "Guide for the interpretation of dissolved gas analysis (DGA) in bushings where oil is the impregnation medium of the main insulation"

[3] IEC 60270, "High voltage test techniques – Partial discharge measurements"

[4] C. Sumereder, A. Gumpinger, "Latest findings at transformer bushings condition evaluation by dielectric response methods," Graz University of Technology, Austria