**Bushings play an important role in the smooth operation of the power grid and when they fail, the residual consequences could be catastrophic**

# Effective bushing monitoring:

## A technical guide to avoiding failure and making critical decisions


### ABSTRACT

Bushing monitoring is an important component of an effective condition monitoring program. Bushings play an important background role in the smooth operation of the power grid, but they are not perfect, and allow for some current to reach the ground: this is called the bushing leakage current. The right monitoring tools and strategy can help record the magnitude and phase of the bushing leakage current and capture information about the state of bushing insulation. This article will address why and how bushing failure occurs and the steps companies can take to protect their systems against bushing deterioration.



### KEYWORDS

bushings, failure, condition monitoring, asset health, maintenance


### 1. Introduction

Bushings, devices that allow conductors to pass through a barrier, may seem like simple and minor components of the power grid, but they are vital parts of the electric supply system – without them, power transformers and circuit breakers would not operate effectively or efficiently, see Figure 1. Bushing failure can cause residual effects that could lead to catastrophic impacts on the entire grid structure [1].

Bushings have an insulating medium that must be sustained to prevent the passage of excess current to the ground, but just like any other part of the power grid, bushings are not perfect insulators. Bushing leakage current is the current that flows through the bushing insulation to the ground. The right monitoring tools can help measure and record the bushing leakage current, including magnitude, harmonic content and relative phase of the leakage currents in a set of three bushings, which provides information about the state of the bushing

insulation. Ongoing monitoring is incredibly important for ensuring bushings effectively do their job.

## 2. Leakage currents: The cornerstone of bushing monitoring

Bushing monitoring relies on the leakage current to indicate the status of bushing insulation. However, the current itself is also dependent on the voltage of the bushing, which may vary phase by phase, with load and system configuration. Such variations are benign and expected, but could lead to false positives if not considered when setting alerts and alarm levels.

Bushing leakage current may be considered to consist of two components: bulk insulation and surface components. The path to the ground through the bulk insulation is of interest here - monitoring surface leakage currents is usually related to pollution monitoring and not necessarily related to bushing deterioration.

Ideally, each leakage current in a set of three would be a sine wave, all three of identical magnitude, and be separate by 120° phase difference. This would mean their sum is zero, but this is rarely the case in practice. For real bushings, the sum of currents is often non-zero, but may be normal for a particular set of bushings in certain circumstances, as shown, for example, in Figure 2. This is a recording of the three individual waveforms for leakage currents measured by a Bushing Data Module (BDM). The data is not sinusoidal, and the resulting sum current is not necessarily zero: but this is normal for this location. Variation in sum current may

**Bushing failures often happen too rapidly for the time-based testing to detect them, because the timescale of these tests is much larger than most bushing failure modes**

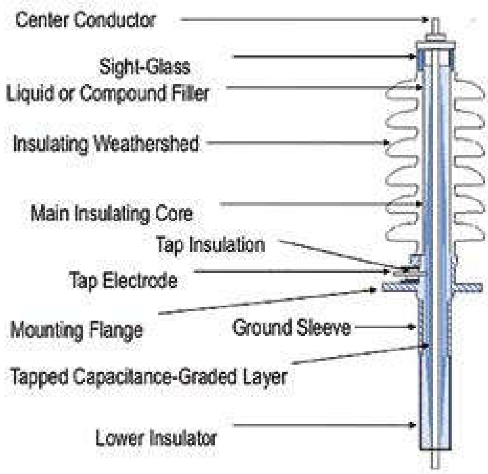


Figure 1. Cross-section of a typical Oil-impregnated Paper (OIP) bushing

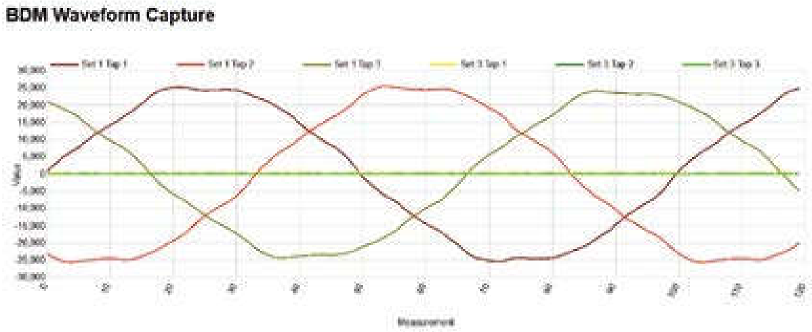


Figure 2. Typical raw bushing leakage current sinusoids

**The right monitoring tools and strategy can help capture information about the state of bushings**

be caused by system voltage variation on each phase, by thermal effects, and be the capacitance difference between non-identical bushings [2].

Measurement of the leakage current should be based on a sample of the actual sinusoid waveform at the bushing tap – this allows for a visualization of that waveform and analysis of harmonic content. Figure 2 shows three typical waveforms recorded by a bushing monitor on a transformer in service. The individual phase currents are similar in magnitude, but not pure sinusoids, containing harmonic content which distorts the waveform.

It is not uncommon on HV networks to have bushing waveforms which are imbalanced; the causes include variations in the system voltage, bushings which are not necessarily equal capacitance, temperature imbalance between bushings, the presence of harmonics, or possibly deterioration in a bushing. The presence of imbalance, by itself, is not necessarily an indication of a bushing problem.

## 3. Failure: Why and how it happens

As the insulation in a bushing degrades, the leakage current changes, possibly in either magnitude or phase, depending on the individual failure mode. It may increase in magnitude and it may change in power factor. When measuring current, it is important to look at both the resistive and capacitive, or reactive, components of the current, for which we require the individual current magnitudes and relative phases. The leakage current is a vector, not a scalar, and must be treated as such by the analysis tools.

Over the past few decades, the overall design and manufacture of bushings has improved, but there are still hundreds of thousands of bushings in service that are in questionable condition. In an analysis of a database in one year, over 1.5 percent of more than 60,000 bushing test results were in a condition such that they needed to be replaced: a $C_1$ power factor either above 1 percent or twice the original nameplate [3]. Some are bushings of known 'suspect' design, but many are not and it is important that teams know how to manage a deteriorating bushing without more offline testing. The addition of more frequent partial discharge (PD) and InfraRed (IR) surveys is one intermittent approach which may provide value. These surveys provide occasional data – once about every six months depending on your testing schedule.

While this is not as good as monitoring, these tests provide more frequent data than time-based tests which may be scheduled years apart – a timescale much larger than most bushing failure modes. The increase in available data from surveys reduces the chance of a failure catching you off guard. The application of a more substantive approach to condition monitoring also provides tremendous results which can detect and prevent deterioration developing into catastrophic failure.

## 4. Condition monitoring in the real world

Widespread application of condition monitoring pays for itself, either in losses avoided or risks reduced. Understanding failure modes, their likely causes and how they can be detected is critical, as well as evaluating the return on investment – how much is the system and what are the chances of detecting deterioration before failure. Over the years two types of failure modes have been observed: 'graceful' and 'rapid onset'.

In Figure 3, the derived power factor value for a bushing is shown with values trended over three time scales: daily, weekly and monthly via a moving average. Daily variations due to system voltage and load effects show up most severely in the daily trend, but are smoothed more in the weekly and monthly – all three trends would come back 'in line' if the bushing was stable and operational conditions constant for a month. Data prior to May 5th is not included.

- **Slow developing failures,** as shown in Figure 3, are slower in deterioration and offer clear indications from a monitored parameter, allowing for several weeks to months of preparation for replacement. Replacement bushings can be identified and strategically used at an opportune moment before failure occurs. Capacitance measurements and sum currents may miss this type of deterioration and can be subsequently confirmed by off line tests and bushing tear down. The variation in power factor had little corresponding variation in capacitance.
- **Rapid onset** relates to failure modes that occur over a very short amount of time, giving minutes to hours of warning. Rapid rise in leakage current over a few hours is a strong indication of imminent failure.

Condition monitoring should be able to handle either type of failure mode. Technical papers [5] and presentations given at industry conferences give examples of both types of failure being detected and acted upon to avoid catastrophic failure. In applying monitoring, we have to set expectations for what values we will get for the monitored parameters: in simple terms, if we don't know what to expect, how can we know it's unacceptable? To set expectations we need to have an idea of the relevant failure modes and the effect they will have on measured parameters.

We also have to consider the differentiation between offline test results and similar online test results. An offline bushing power factor test will be performed using a very well controlled voltage reference applied at the bushing, but usually at less than rated voltage for the bushing. An online test is at rated voltage and the power factor response may differ due to 'tip-up' and temperature effects. Tip-up is the increase in measured bushing power factor when the applied voltage for the test is increased. This is a common test, used to show the effects of insulation deterioration and contamination. A reference voltage may be available to provide an indication of operational variation – it provides a useful reference in the form of a Root of Mean Square (RMS) value to apply to capacitance calculations – removing some of the variations for each phase. In theory, the reference voltage for each phase would also be useful in determining the power factor of each individual bushing, but this is dependent on the accuracy of the voltage measurement and the relationship between the location of the voltage reference and the bushing in question. Where a reference voltage is available, it is now also a measured parameter rather than a highly controlled value applied in offline tests. There are now sources of error in the voltage measurement which add to the overall measurement errors – including the accuracy of the voltage transformer, the phase angle offset due to transformer tap position – and can lead to online measurements being quite different to offline measurements.

So, we must ask the question: what result are we expecting? If we know what to expect, we can set alert and alarm levels accordingly – and appropriate response plans for those notifications.

## 5. The three C's of condition monitoring

Effective monitoring will track parameters associated with suspected failure modes. If the failure mode is fast, the monitor may not respond in time to give appropriate warning and allow for intervention. The nature of bushing failures is that they are often very rapid and teams need to have an agreed upon response plan established ahead of time so they are ready to respond.

Condition monitoring requires the three C's: control, context, conclusion [4]. By controlling the measurements made and understanding the measurement context, we can draw three reasonable conclusions:

- Poorly **controlled** or loose measurements will provide data which cannot be relied upon and may lead to inappropriate decisions.
- Understanding the **context**, whether operation load and voltage or the presence of nearby sources of reactive power, can alter analyses of bushing leakage current considerably.
- **Conclusions** need to be actionable and timed. We apply condition monitoring to support decisions and when an alert or alarm is raised, we should have an appropriate action plan in place to respond – an action and a timescale, with personnel to carry out the action.

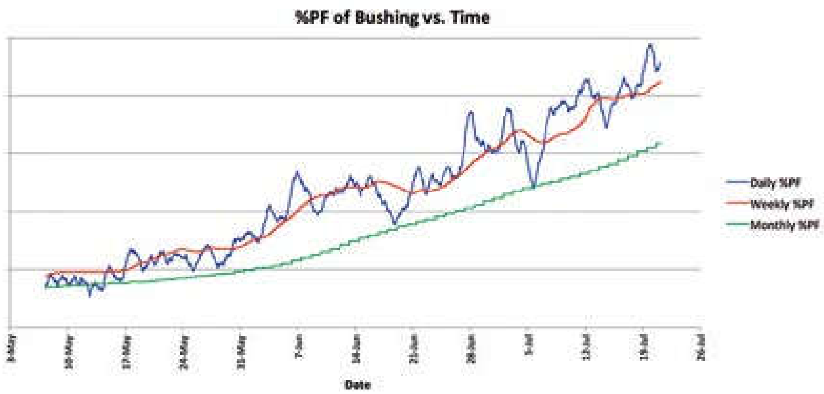


Figure 3. Daily, weekly, and monthly power factor trends for a bushing known to be deteriorating

> **Contextual information about ambient and system operating conditions can improve analyses**

## 6. Bushing deterioration detected: Rapid onset failure averted

To highlight the importance of agreed-upon action plans, let's look at one case at a transmission utility with suspicions about several bushings that were monitored [5]. When the monitoring system was installed, it was to detect rapid deterioration. An action plan was developed and agreed upon by relevant parties. If a high-level alert was generated, the transformer would be switched out within two minutes and a local offline test performed to confirm the online measurements.

Over time, the monitoring system had shown variation in online power factor and capacitance for many units. Early one morning, the monitoring system gave a high-level alarm notification, and as planned and agreed, the unit was rapidly switched out of service so offline tests could be performed. The data showed a large increase in leakage current over just a few hours for one bushing in a set of three, as shown in Figure 4. The leakage current magnitude rose from ~7 mA to >10.5 mA in a space of two hours. In accordance with the agreed plan, the transformer was deenergized to allow for offline tests to confirm the online results.

Offline testing confirmed the online results and the bushing was removed from service. Power factor had risen by a factor of more than three and capacitance by almost 50 percent. A subsequent forensic tear down showed puncture marks and burning close to the edge of many of the foils. Given the insulation status, the time taken for the leakage current to increase and historic background on these bushings, it was concluded this bushing had just a few hours before catastrophic failure. That situation was avoided through acting on a pre-arranged mitigation strategy.

This case shows successful condition monitoring that relies on a few critical things (the three C's):

- An understanding of the need to **control** the measurement to produce valid results

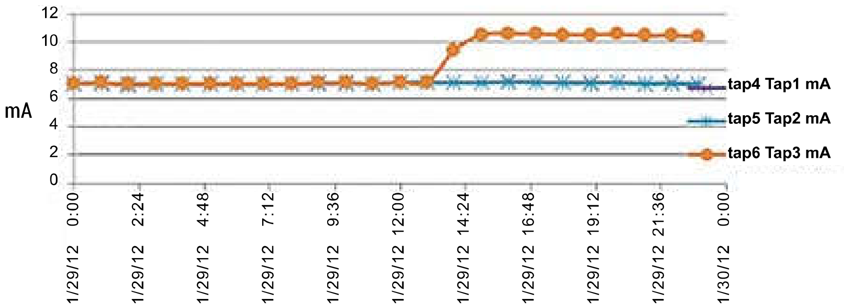


Figure 4. Detecting rapid onset failure mode

## Having an agreed upon plan of action based on data and failure modes can help teams get the most from monitoring

- A **context** for the data so results can be analyzed considering all impacting parameters
- Actionable **conclusions** which permit intervention using prearranged and agreed upon plans

There must also be a mechanism for implementing change, which could be a target group of bushings identified for monitoring based on measured offline test parameters and industry knowledge.

## 7. Good data yields good decision-making

When applied properly, the benefits of condition monitoring outweigh the challenges of implementation, but to make good decisions, there needs to be a solid foundation of the most comprehensive data possible [6]. It is important when taking bushing measurements to have the raw sinusoidal waveforms available, the magnitude of individual currents and relative phase and an expert system analysis, which uncovers what is 'normal' at an individual location.

In Figure 5, the level of PD detected through a bushing is trended and overlaid with the bushing leakage current for the same bushing. The bushing leakage current is plotted in yellow, and scaled in mA on the left hand vertical axis; the PD level is given in dB values on the right hand vertical axis for the "Peak to Average Power Ratio" (PAPR) for each PD recording; a measure of the severity of the PD signal, normally expected to be between about 10 and 15 dB. The bushing is on a Generator Step-up (GSU) transformer, which had recently been maintained, along with the associated unit transformer and generator set. As the generator is brought back online, and 'run up and down,' the bushing leakage current rises and falls as the voltage on the bushing changes with the generator. There is some minor PD activity, measured through the bushing, at about 8 a.m. and again at about 10:30 a.m. However, as load is brought up on the generator – something which has little effect on the system voltage – there is a substantial rise in PD activity at 1 p.m. the PAPR value rises to about 45 dB, or about 1000 times the power level expected in 'normal' operation.

The data shown in Figure 5 is a significant rise in PD levels associated with the energization of the transformer and ramp up of load: highest level alerts were generated and texted to the engineers. This is a clear indication of a possible issue – so what's the plan?

This is the time to act on the plan, and to respond to the situation. As can be seen in Figure 5, the generator was 'run down' and taken offline – the leakage current drops to zero and the PD levels return to 'normal.' A subsequent investigation considered both monitoring data and contextual data from the transformer and the generator. The source of the PD was, in fact, in the generator itself and was addressed through maintenance; subsequent reenergization and ramp up of the generator yielded no PD signals via the bushing.

This case raises some interesting points about monitoring in general, and bushing PD monitoring in particular: does the data relate to a failure mode, and what could cause the data to change? In the case summarized in Figure 5, the bushing PD detection was 'valid' but the contextual information, associated and synchronous temperature rises in the generator, indicates a source likely to be outside of the bushing, and even outside of the transformer itself. With more contextual information available to make a decision, a better decision is likely to be made.


Figure 5. Bushing leakage current and PD levels on energization of a GSU transformer

**The response plan must include the interest of all stakeholders in the asset, including engineering, operations and asset management**

## Conclusion

Bushing failure often happens very rapidly, often so quickly that offline testing will not detect the deterioration in time for intervention. Online monitoring provides a means for filling in the gap between offline testing and gives the asset owner more information for making informed and important decisions. Contextual information about ambient and system operating conditions can improve analyses. Having an agreed upon plan of action, and one that is based on data and failure modes, can help teams get the most from a monitoring system. It is imperative for any owner or operator to plan for whatever situation the system may be reporting, and have a strategy in place around how to respond – and this response plan must include the interest of all partners that have a stake in the asset, including engineering, operations and asset management.

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**Bushings are usually subjected to stress factors such as heat and transient overvoltage in service**


## ABSTRACT

Standard online monitoring systems for bushings must, in particular, consider the dissipation factor and the main capacity ($C_1$) of the bushing. Typically, the known principles have problems due to network imbalances and temperature influences caused by the environment and load.
A new method, described in this article, Double-Reference Method, monitors the changes in capacitance and dissipation factor in a three-phase system so that the temperature dependence is eliminated, since the algorithm continuously incorporates all three bushings into the mutual monitoring. Furthermore, the signals of the respective voltage transformers are used as a reference for detecting the symmetry of the three-phase mains voltage. Only if the grid symmetry is within a defined bandwidth, the measurements are taken into account. So, this method ensures that the influence of temperature and voltage fluctuations on a bushing monitoring system is effectively limited by the cross checking of values.



## KEYWORDS

online monitoring, power transformers, high-voltage bushings, condition monitoring