

Bushing Failure Prevention Through Online Monitoring

by **Marco Tozzi**



The role of online monitors is not to eliminate standard Capacitance/Power Factor test or to provide identical results as offline tests. The real benefit of online monitors is their ability to detect anomalies under real operating conditions that otherwise would not be detected, and then follow it up with the best suitable offline test for investigation.



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Introduction

According to statistics published in IEEE, IEC and CIGRE, bushings contribute to roughly 15-30% of transformer failures worldwide. In more than 40% of cases the failure is of violent nature followed by catastrophic consequences, such as fire, tank rupture and explosions. In particular, 30% of generator step-up transformer failures are caused by a bushing malfunction and more generally, bushings are the third single cause of transformer failures after winding and OLTC [1].

While DGA can help in assessing the condition of the main tank, it fails to provide any valuable information about the bushing health. Therefore, dedicated monitoring systems must be applied. These systems are connected to the test or voltage tap to measure and analyse the current flowing in the main capacitance C_1 , which varies in amplitude and phase angle depending on the issues found in the bushings.

It must be understood that the role of online monitors is not to eliminate completely standard Capacitance/Power Factor (C_1 /PF) test, nor to provide the same identical results. The real benefit of online monitors is their ability to detect anomalies under real operating conditions that otherwise could not be detected, and then trigger the best suitable offline test for investigation.

Some typical questions that are raised are, "Would you expect the offline measurement to be identical to the results of the online monitor?" The answer is: Potentially yes, but it depends on what the defect is, which offline measurement and in which testing condition, since there is not a single test or a single failure mode. Figure 1 shows a bushing which is in a critical condition due to the

detachment of the conductive strip that connects the first foil layer [2]. The bushing was showing perfect Capacitance and Power Factor values in the offline test and it would have been returned to service based solely on these results. However, DGA showed >3000 ppm of C_2H_2 clearly indicating that the bushing needed immediate replacement.

Thus, it is not only about C_1 /PF.



Figure 1. Discharge within bushing not detected by standard offline C_1 /PF test [2].



Figure 2. Bushing adaptor connected to voltage tap

Indeed, selecting the proper offline test and combining the results with the online data will provide a more complete picture of the failure mode. Knowing not only that there is a problem but also what the problem is, can help the asset manager to prevent failures in similar bushings (from the same OEM, or of the same age or voltage, etc.) earlier by recognizing the failure mode whenever similar conditions are detected, and ultimately, to make better choices

in the future when specifying a new bushing.

Successful cases have already been published, showing the ability of online monitors to detect early stage of degradation due to sudden capacitance changes [3] or internal contamination from metallic particles [4]. In this article, we will focus on a case study highlighting moisture contamination, where

not only the bushing was saved but where the online monitor reacted to the real operating condition and provided a more accurate diagnosis than standard offline tests.

For the sake of clarity, the terms Power Factor (PF), Tandelta, Tangent-delta and Dissipation Factor are used interchangeably in this paper.

Bushings and Diagnostic Procedures Basics

Transformer bushings are made of a central conductor wound with insulating paper and conductive layers. The succession of insulation and conductive foils forms a cylindric condenser which controls the electrical field along the length and radius. The conductive layers are typically made of aluminium foils but, in some cases, they might be manufactured with conductive paint, printed semi-conductive ink or semi-conductive paper. There should be no air or bubbles present between the layers, so the paper/foil system is first dried and then impregnated with either oil (Oil Impregnated Paper – OIP type) or resin (Resin Impregnated Paper – RIP type). From the electrical point of view, regardless of the type, the bushing appears as a capacitor made of a number of capacitances in series, one in each layer, with the total equivalent capacitance C_1 in the range of hundreds of pico-Farad.

Causes of bushing failures are related to the loss of bushing properties, i.e. an inability for a bushing to act as an "ideal" insulating medium between the high voltage and the ground. This can happen for multiple reasons, such as:

- Ingress of moisture – increases the losses and causes the capacitor to become conductive
- Ingress of solid contaminants – increases the losses and causes the capacitor to become conductive
- Oil leakage (OIP type) – leads to electrical discharges
- Electrical short circuit between the layers – increases capacitance and creates a conductive channel
- Presence of voids, cracks and delamination between layers – causes Partial Discharges and insulation erosion, ultimately creating conductive channel and short circuit of the layers
- Surface cracks on the porcelain

Visual inspection and Thermal/IR scan are typically conducted on a monthly and annual basis, respectively, while traditional electrical tests are performed according to the time-based schedule, typically in four-to-eight-year intervals, including:

- Offline capacitance measurement
- Offline PF measurement

Additional tests are done exceptionally, not as a routine:

- Dissolved Gas Analysis, including moisture
- Oil quality
- Dielectric Spectroscopy
- Partial Discharges
- Tandelata tip up
- Tandelata at different temperatures

In terms of actions, there are no standards defining what action needs to be taken depending on the results of the tests. However, there are a few rules that utilities commonly follow:

- Bushing is replaced when the measured PF is more than twice the nameplate value
- Bushing is replaced when there is acetylene in the bushing oil
- Bushing is replaced when the measured Capacitance is X% higher than nameplate value, where X depends on the number of layers. Since the number of layers is not known and different tables are provided by bushing OEMs, a general rule of thumb is to take an action whenever $X=10$ regardless of the bushing voltage, while further investigation (and contact with OEM) is recommended when X is between 1 and 5 for bushings >100 kV, and between 5 and 10 for bushings <100 kV.

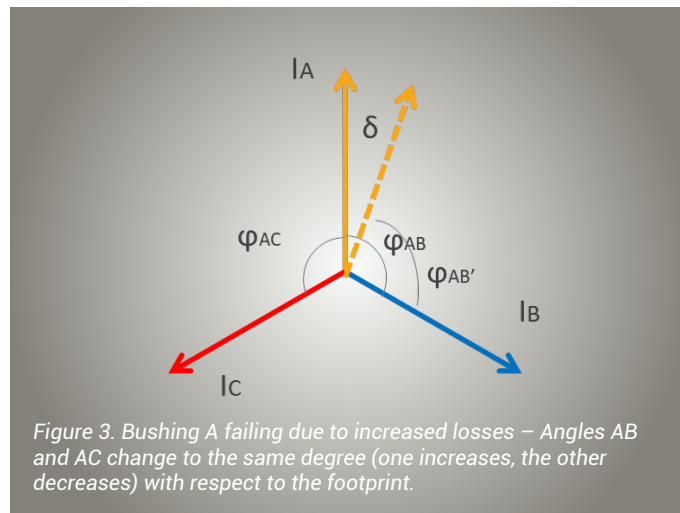


Figure 3. Bushing A failing due to increased losses – Angles AB and AC change to the same degree (one increases, the other decreases) with respect to the footprint.

Online Bushing Monitor Principle

Bushings can be monitored by installing an adaptor at the bushing test/voltage tap, where an impedance is connected between the pin and the ground (typically a resistor or a capacitor, depending on the vendors), thus in parallel to Bushing C_2 and in series to Bushing C_1 . The voltage/test tap pin must always be grounded, either directly or through the impedance to prevent it from floating, at free potential. For this reason, additional protection must be included inside the body of the adaptor (not just in the monitoring system at ground level).

The cases described in [2], [4] and in this paper were captured with a monitoring system that uses the

so-called Relative Method. This method is based on the analysis of the amplitude and angle of the current that flows in the bushing C_1 and through the impedance at the test tap and its comparison with bushings in the same transformer or in other transformer connected to same busbars.

The principle is that whenever the bushing properties are changing, due to an internal short circuit or increased losses, the current of that specific bushing (and, thus, the voltage at the test tap) will increase accordingly, while the current of the other bushings will not. At the same time, the angle between the current of the failing bushing and the current of the other two bushings in the same winding (ideally 120 degrees) will change. The proportion between the change in the current amplitude and the change in the angles depends on both the failure mode and the degradation stage.

So, the relative method implies applying averages to reduce the day-to-day fluctuations due to grid imbalances and calculating a footprint after a learning period (after an hour, a day, a week or a month).

The new readings are then compared to the footprint in order to determine relative variations.

The challenge of the relative method is mainly on the PF side and lies in understanding whether the increase of the phase angle is caused by a failure or by normal fluctuations in the grid. Indeed, the angles between the bushings can normally swing between +/-0.5 degrees, whereas if there is a problem in the bushing, the angle variation could be only 0.1-0.2 degrees, and potentially masked by normal fluctuations. For this reason, bushings in the same winding and bushings in the same phase (in Y-Y or Δ - Δ connection) are used as a reference under the hypothesis that three bushings of the same winding cannot fail together simultaneously.

Despite the challenges, the relative method presents significant advantages in comparison to the other available method, known as Referenced Method or, misleadingly, Absolute Method. This method consists of collecting the reference directly from the Voltage (VT) or Potential Transformer (PT), in the following manner:

- Relative method allows the bushing monitoring to be applied in every situation (provided test/voltage taps are available), while the referenced method requires the accessibility to the voltage transformer, which is not always possible.
- Relative method has significantly lower cost, considering that the reference method requires additional hardware, very long cables to connect to VTs and higher cost of installation (nine bushings would require connection, one per phase, in three separate VTs), all contributing to a higher cost of the solution.

contamination process can last for weeks or even months.

Data Interpretation: Building Trust

The relative method shows a very positive cost-benefit balance. It is, however, important that the results that the system provides are well understood to build the required confidence in managing the information and alarms. In particular, there are three important things to understand:

1. The online monitor does not measure C_1 /PF quantities, nor does

There is a general misconception that online monitors should report data that perfectly align with the results of a standard Capacitance/Power Factor offline test.

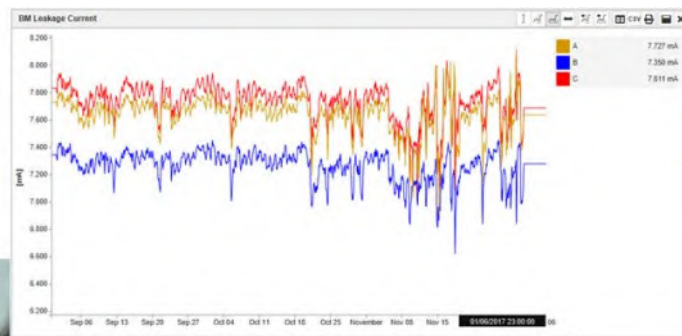


Figure 4. Bushing tap leaking due to worn gasket behind the test tap, detected by online monitoring and not by standard C_1 /PF test

In terms of performance, the relative method is comparable with the reference method with respect to the detection of capacitance changes [2] (the % change in the current due to a short circuit is higher than typical voltage fluctuation) or significant PF changes, while it can be slower in detecting small PF changes due to the effect of averaging. However, it must be stressed that the PF changes are typically caused by slowly developing failures since the

- it replace the C_1 /PF test typically done offline. The measured parameters are different, and the measuring conditions are different.
2. What the online monitor measures and monitors is the bushing current (sometimes called leakage current) at the test tap, under the assumption that the majority of the issues in the bushing will reflect in a change of the current in either amplitude or phase angle.
3. Not only are there two failure

modes (capacitance increase and PF increase), there is also more than one way to assess the bushing offline.

These three principles are extremely important to understand before applying an online monitoring program. Indeed, there is a general misconception that online monitors should report data that perfectly align with the results of a standard C_1 /PF offline test. However, an increase in the monitored current does not necessarily mean that there is a capacitance change, just as a change in the

current angle does not mean there is a definite moisture ingress. There is actually a significant variety of possible failure modes and defects that could lead to a change in the monitored current, not just short circuits and moisture ingress.

Failures can happen in each of the bushing components, with a multitude of failure modes depending on the nature of the contaminant, the location of the defect, the amount of insulation involved and the root cause (thermo, electric, mechanical stress, ageing, constructive defect, etc.).

Furthermore, some defects could lead to a temporary change in bushing properties during real operating conditions as a result of temporary changes in the load, temperature, pressure or humidity, and it could be difficult to spot the defective condition during the standard C_1 /PF offline test, which is typically carried out at just one temperature (ambient) and one voltage.

To illustrate, Figure 4 shows a test tap leaking oil: This was found in six bushings and in three of them it was captured through online monitoring. The symptom was a continuously dropping leakage current. The system gave an alarm of low current and this triggered an inspection where the problem was identified. Again, the standard test here would not have highlighted any issue since both PF and capacitance measured offline were matching the nameplate values.

CASE STUDY: OIP bushing replacement after PF increase due to moisture ingress

Online Data

A bushing and partial discharge monitoring system was installed in 2015 on a three-phase transformer in North America. The monitor was applied only to LV bushings due to a higher failure rate experienced in recent years and as part of a replacement plan of LV bushings, in particular the U-Type.

The installed device was continuously monitoring the bushing currents and partial discharges from both the main tank and bushings using properly designed tap adaptors installed at the test taps. The acquisition was continuous (*not scheduled*), simultaneous in all phases and results were summarized every hour. The bushings, as shown in Figure 5, were from McGraw Edison 1988, OIP, 34.5 kV, around 590 pF of Capacitance.

Figure 6 shows the unprocessed data of the leakage current amplitude (top chart) and angles between bushings A and B (bottom chart, black line) and between bushings A and C (bottom chart, red line). It is easy to note that for several months the readings were very stable. After May, the angle between the bushings A and B started to increase while the angle between bushings A and C remained constant, thus suggesting that the change was related to some issue in bushing B. Looking at the readings of the current we notice that the leakage current of the bushing B also started to increase slightly after June, confirming something happening in bushing B.

Figure 7 shows the processed data using the algorithms embedded in the online monitoring system aimed at converting the current and

angle readings in relative changes of Capacitance and Power Factor. It was estimated that the change occurred only in bushing B, showing a relative increment of around 5.5% from the footprint, which means that if the nameplate value is 0.53%, the actual tan delta is estimated to be higher than 6%.

Offline Investigation

The utility switched off the transformer to perform an offline test and the PF was found to be about four times higher than the nameplate, with a measured value of 1.99% while the nameplate is 0.53%, clearly justifying a decision for a bushing replacement.



Figure 5. Bushing adaptor connected at the 34.5 kV OIP bushings

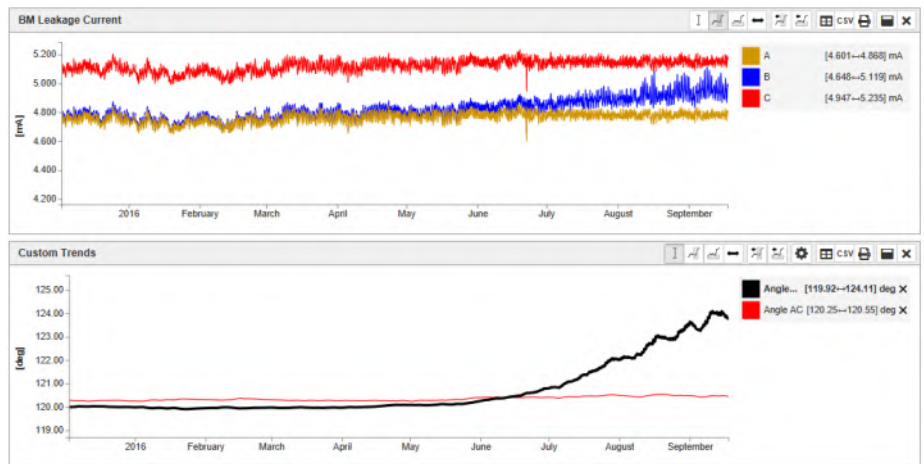


Figure 6. Test tap current magnitude (top) and angles recorded and summarized every hour (bottom). AB angle increased by about 4 degrees in 6 months.

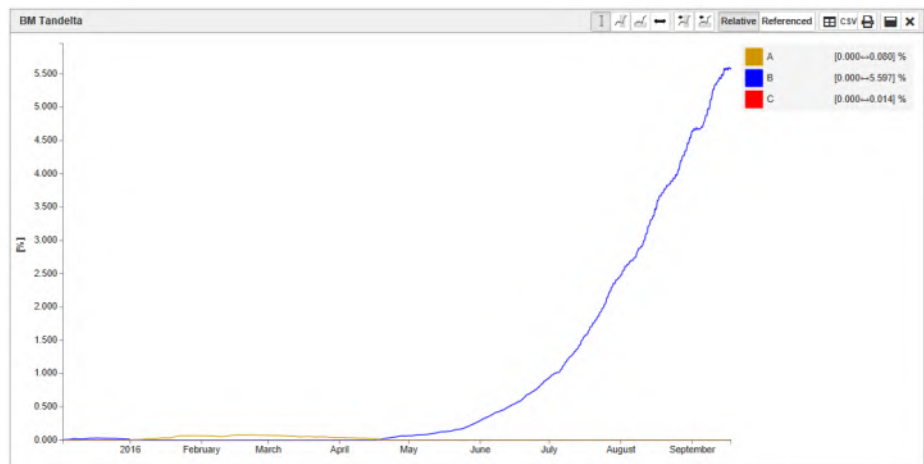


Figure 7. Relative PF increase displayed on the monitor.

However, although the offline measurement confirmed the presence of an anomaly as triggered by the online system, it is interesting to note that the measured value is three times lower than the one indicated by the online monitor. In order to further investigate this difference, the bushing was removed and sent to a third-party laboratory to perform additional tests:

- Partial Discharges
- Dissolved Gas Analysis
- IR Scan
- Moisture Analysis, and
- PF vs. Temperature

The partial discharge test, DGA and IR scan did not show any critical values. However, the other two tests showed very interesting results. The bushing was tested at ambient temperature (15°C) measuring 1.8% for PF, which was very similar to the values measured offline by the utility.

Then the bushing was immersed in oil and the oil was heated up to 60°C for two hours. After 1.5 hours the bushing was tested again showing PF equal to about 9%, i.e. almost 20 times the nameplate value. After reaching the maximum temperature the bushing was left to cool down and PF was measured again at different temperatures. The final profile of the PF with temperature is shown in Figure 9, where both oil and bushing temperatures are reported. The exponential rise with temperature confirmed the critical stage of the insulation and, most importantly, the values measured at 30-40°C range were perfectly aligned with the variation measured by the online monitoring system in real conditions. Indeed, after May the ambient temperature started to rise, well exceeding 30°C, and thus causing the bushing PF to increase up to 6 -7%. The test demonstrated that the difference between the online and offline results were not caused by deficiencies in the monitoring system.

Quite the opposite, the PF reading at the real operating temperatures were correctly estimated and reported, while the offline test was done in a different condition and with lower oil temperature.

Failure Mode Investigation

Whenever bushing PF exponentially

Arrester		Exciting Current		Double Ratio		Turns Ratio			
all		Bush C1/C2		Bush Hot Collar		Insulating Fluid			
C2									
NP %PF	NP Cap	Test kV	mA	Watts	% PF Meas.	% PF Corr.	Corr. Factor	Cap (pF)	Rtg
0.53	592	10.00	2.205	0.1240	0.56	0.58	1.04	584.89	D
0.53	591	10.00	2.232	0.4270	1.91	1.99	1.04	591.91	I
0.53	635	10.00	2.360	0.1220	0.52	0.54	1.04	625.98	D
0.48	582	10							
0.53	591								
0.53	635								
0.48	582								

Figure 8. Offline test result showing bushing B having high PF

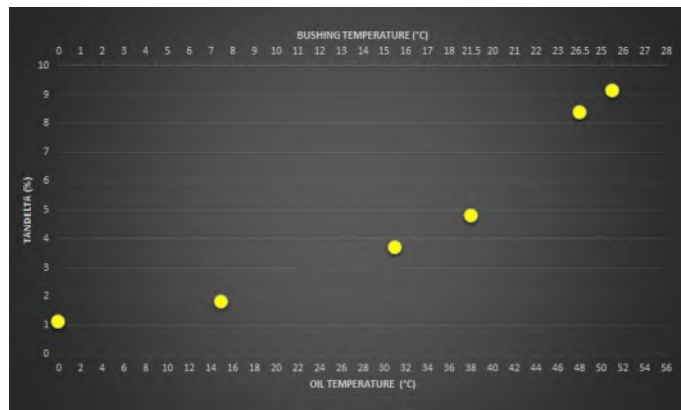


Figure 9. Offline PF test results at different ambient and oil temperatures showing that at normal operating oil temperatures (30-40°C) the PF readings match the online results.

increases with temperature, this might indicate high conductive losses due to the presence of moisture [5]. As an example, it has been published that the power factor can increase from 0.3% at 20°C to 1.0% at 70°C with 2% water content [6]. By looking at the curves published in [7] and [8] and comparing it to the lab measurement of the bushing under investigation, it is possible to speculate that the bushing had an excess of moisture above 4% (Figure 10).

A similar conclusion can be drawn from the oil result. An oil sample from the bushing was analysed at different temperatures, showing 12 ppm at 15°C and 19 ppm at 2°C. Putting the recorded value in the moisture equilibrium plot from Oommen [9] it is clear that again the moisture is well

above 4% (Figure 11). In particular, the sample at 2°C would fall outside the chart suggesting more than 10% of moisture.

Conclusions

Application of online bushing monitoring can prevent catastrophic failures which are responsible for up to 30% of transformer failures.

Cases have already been published [3,4] showing the online monitoring system was able to detect fast capacitance changes or power factor increases plus partial discharges due to metallic particles contamination. The case described in this paper shows the online monitoring system is capable of detecting a failure due to moisture ingress, which increased the bushing power factor up to 10 times the nameplate value.

Not only that, this case demonstrates the need to build trust in online monitoring systems since they can detect anomalies in real time under real operating conditions.

Such anomalies do not necessarily lead to a permanent power factor or capacitance change, and in many cases, could not be detected using the standard approach of testing offline C₁/PF at just one temperature and one voltage.

Relative changes of the monitored current, whether in amplitude or angle, should trigger alarms aimed at reviewing the data and then selecting the most appropriate offline test and method among a variety of possibilities, including DGA, DFR, Tan Delta Tip Up, etc. Thus, online monitors do not eliminate or replace offline tests. As a matter of fact, by combining online and offline results it is possible to better understand the failure mode and provide clear prescriptive actions for the most effective decision-making process.

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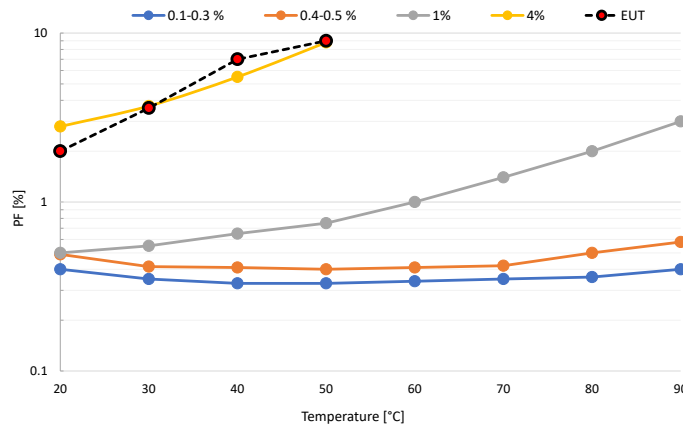


Figure 10. Bushing PF versus temperature. Redrawing of [8] comparing the results of the Equipment Under Test (EUT)

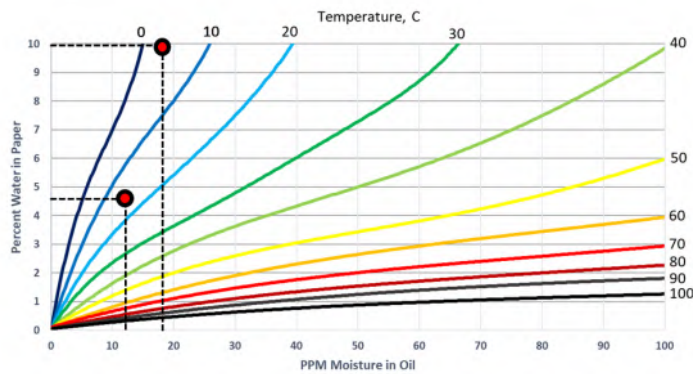


Figure 11. Moisture equilibrium isotherms (redrawing from Oommen curves [9]) showing that estimated water for the tested bushing exceeds 4%

Online monitoring systems should not eliminate or replace offline tests. By combining online and offline measurements it is possible to better understand the failure mode and provide clear prescriptive actions for the most effective decision-making process.

