Figure 1: Planning ahead for installation

Bushing Monitoring: What Were You Expecting?

by **Tony McGrail**

Well? What were you expecting when you bought a bushing monitor? Let's go through things in stages using a bushing monitor able to give individual bushing power factors and capacitances. Oil DGA, temperatures, PD measurements may also be very valuable diagnostic techniques, and the same approach as discussed here is recommended in those applications.

Step back…

Ok, let's step back a moment: I'd hope you have a few things in place at the outset after your organization decided to monitor bushings in order to make sure you get value from your monitor.

a) A business case which shows that the benefit of the monitor, or monitors, outweighs the cost of: installation, commissioning, and monitor upkeep over time to ensure good monitor performance. You need data to show that the application of the monitor/s has reduced risk and/or allowed for controlled removal of suspect bushings.

A positive business case for some specific bushings is usually easier to generate as they have specific, possibly accelerated, failure modes.

b) A management plan for the monitor – will it be installed at the factory, removed for shipping, re-installed in the field? Who is responsible for ensuring the monitor is shipped safely and arrives in full working order? If any parts of the system are changed or removed, say for offline testing of the bushing, who ensures that everything goes back together correctly? And the same questions for the sensors which attach to the bushings? For example, see Figure 1 where, on the left, there is sufficient space for a bushing tap sensor, which houses the multiple redundant protection components and armored cable, whereas on the right there is insufficient space for the sensor; Figure 2 shows a low clearance adapter for such situations, which allows for some of the protection to be moved away from the bushing tap.

c) An understanding of what the monitor can do, and what you need to do to allow the monitor to do its job effectively:

i. What measurements does it make? With what accuracy? How do the raw and derived data values relate to bushing failure modes? How much warning do you get?

ii. How is data stored? Where?

iii. What are the algorithms used to derive parameters such as power factor and capacitance? How do the algorithms work?

iv. How does it communicate alerts? To whom? Locally and/or remotely, what network connections are needed?

Photo: Doble, Shutterstock

Tony McGrail is Doble Engineering Solutions Director for Asset Management & Monitoring Technology, providing condition, criticality and risk analysis for utility companies. Previously Tony has spent over 10 years with National Grid in the UK and the US; he has been both a substation equipment specialist and subsequently substation asset manager, identifying risks and opportunities for investment in an aged infrastructure. Tony is a Fellow of the IET, a member of the IEEE, CIGRE, ASTM, ISO and the IAM, and is currently active on the Doble Client Committee on Asset and Maintenance Management and a contributor to SFRA, Condition Monitoring and Asset Management standards. His initial degree was in Physics, supplemented by an MS and a PhD in EE followed by an MBA.

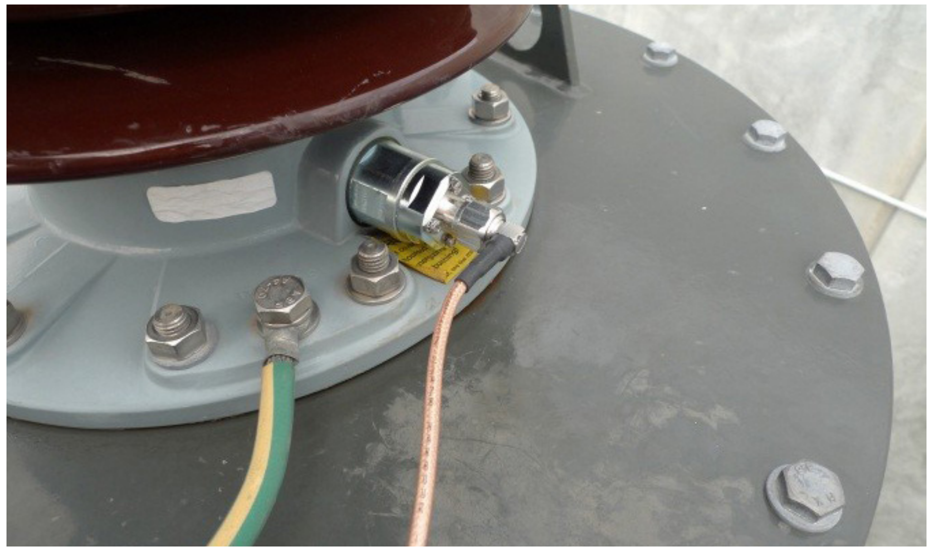

Figure 2

d) An understanding of the individual applications – bushing type, location, etc. – which will affect the measurements generated, as there may be different failure modes which apply for GE Type U as opposed to Trench COT(A), for example. At this point we are beginning to look at expectations: what do we see for this particular bushing? For this set of bushings? Do we know what is normal? What is acceptable?

e) Alert management plans:

  i. A set of alert levels for each application based on the bushing type and data available from the monitor which give timely indication of bushing deterioration: three levels at low/medium/high are not uncommon.

  ii. A set of response plans for each alert including what to do, who does it, by when, with appropriate audit details as per an asset management program, including a post alert review

f) Condition monitoring needs to be seen as part of the asset management strategy of the organization and, as such, it's something 'we do' not just something 'they do': 'condition monitoring is not just a box with lights on'(1, 2). A written statement of condition monitoring strategy and policy would be a useful reference.

Condition monitoring needs to be seen as part of the asset management strategy of the organization and, as such, it's something 'we do' not just something 'they do': 'condition monitoring is not just a box with lights on.'

Step Forward

With everything in place and data being generated and keeping an eye on alert systems, what does your data look like?

As an example, we'll look at a relatively common approach where we use the nominal system voltage and the nameplate bushing capacitance to calculate an expected leakage current magnitude:

  i. simultaneously record the current waveforms for each of three bushings in a set

  ii. Use the waveforms to derive the individual current rms and relative phase

  iii. Compare the derived current values with the calculated expected values

  iv. Set alerts if that current is higher than expected, or lower than expected – by how much depends on the individual application, but a consistent variation of, for example, 2% could be a useful indicator of bushing deterioration, but could also indicate a sustained variation in system voltage

Figure 3 shows the leakage current magnitudes of a set of three bushings recorded over 7 days; note the variability of the individual currents and how the magnitudes vary both individually, with respect to previous values, and relatively compared to other bushings in the set: sometimes the red and blue traces are close together, sometimes they are further apart; sometimes all three change suddenly. What causes these variations?

So, with everything in place and data being generated and keeping an eye on alert systems, what does your data look like?

The causes could include things such as system voltage variation, tap position variation, temperature effects, surface leakage current effects due to contamination on the bushing, bushing deterioration. A small change on all three bushings could well be a system voltage variation; a larger change could be a tap changer operation.

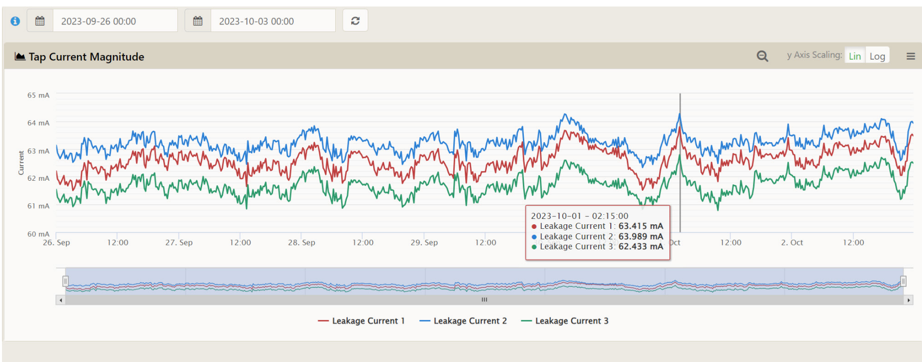

Figure 3: A set of 3 bushing Leakage Current Magnitudes over 7 days

Photo: Doble, Shutterstock

Overall, we need to get to know not only what is expected for a particular application, but also what is normal and acceptable. Then we can tune alerts to be more sensitive to significant variations.

The same approach can be applied for the relative phase angles: we expect them to be 120°, as shown in the left of Figure 4, but this requires a perfectly balanced system and three identical system voltages on three identical bushings.

If one of the bushings in Figure 4 starts to deteriorate and its power factor rises, its phasor will move closer to its driving voltage, which would be a clockwise move, as shown on the right of Figure 4. This results in one relative phase decreasing, one relative phase increasing by the same amount as the other decreases, and one stays the same. However, it should be noted that the 10° variation in phase angle is immense – a variation of 0.5° is not uncommon, but a deteriorating bushing would likely supply only 0.1°.

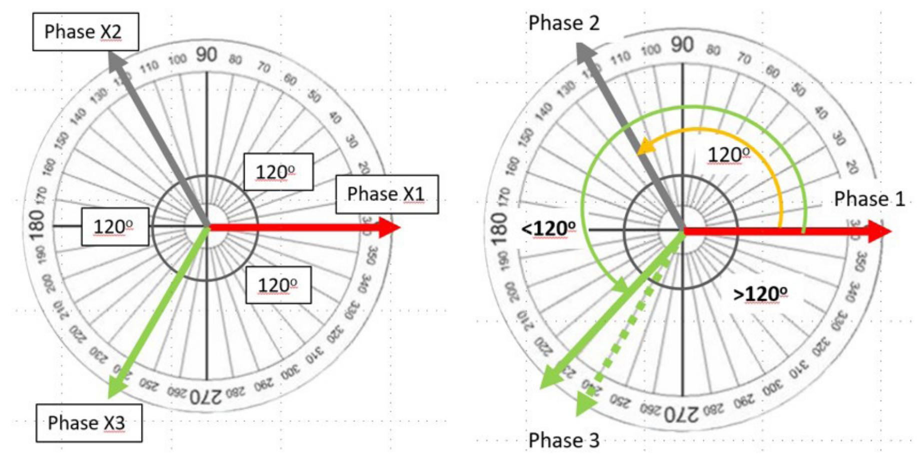

Figure 4: Three Phasors giving relative phase, ideally 120°

Figure 5 shows the 'natural' variation in phase angle on a set of three bushings over a 4-day period, measured hourly.

The phase angles in Figure 5 vary in a similar way to the currents – they are not constant relative either to their own history or relative to their neighbors. But the fact that Bushing 2 is the one thing common to the two relative phase angles which vary is a strong indication that it is a possible cause of the variation.

We can also use the relative phase angles to work out the power factor of the bushing which seems to have changed. We do have to make some assumptions which we will have to check if an alert comes in:

  i. we expect the system voltage to have a 120° difference between phases, which is not always true, and is affected by, for example, variations in system MVA/MVAr ratios, the proximity of static var compensation and tap position

  ii. we expect, given the relative infrequency of bushing failures, that only one bushing will deteriorate at a time.

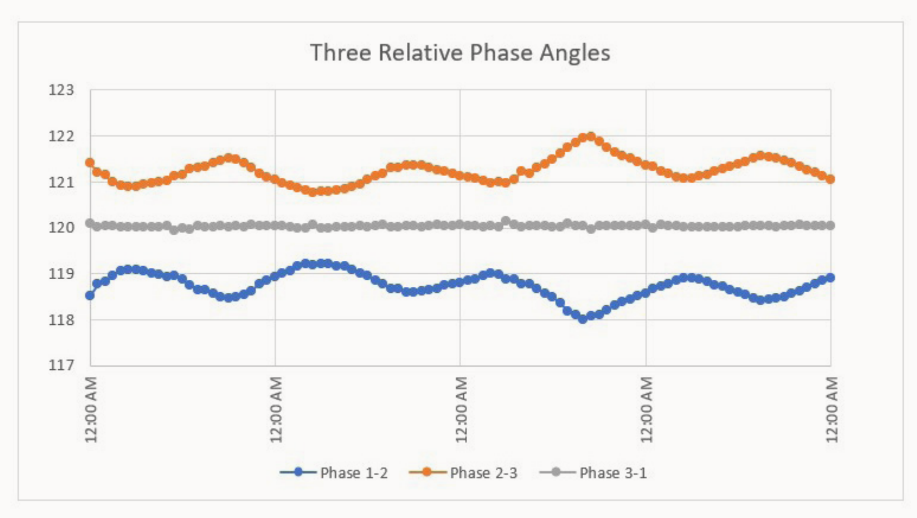

Figure 5: A set of relative phase angles over 4 days

iii. We will use the relative phase angles to calculate a power factor for each bushing and we expect, in general, that the bushing power factor will rise as the bushing deteriorates. This is not always the case and causes of a fall in apparent power factor could include both a rise in surface contamination on the bushing, or a build up in internal contamination providing a resistive path to ground (3, 4)

These assumptions are good in general, but need to be borne in mind as we review data, especially as we work out what is normal. We can set alerts on the relative phase angles to indicate a change of more than a particular value. That value will depend on what is normal for your application: but set an alert level to generate more alerts to begin with, then loosen or tighten the level to provide more meaningful information when we recognize 'normal'.

We use the relative phase angles and the assumptions to derive a power factor for each bushing. Given that the background variability in the phase angle is large, we can add smoothing using averages over a day, a week and a month so as to remove the 'noise' in the resulting power factor values. We can then apply three alert levels to each of the daily/weekly/monthly trends. Figure 6 shows the smoothed values for a single bushing over a 7-day period.

In Figure 6, the monthly power factor is an almost constant value, while the weekly has some low variation, and the daily much more. This is common, in practice, and reflects the variation on the system plus any variations related to the bushing itself.

In addition, for any measurement that we make, we should also be able to look at not just absolute measures such as picofarads and milliamps, but also percent variations to the value from a baseline, as a change of 1 mA on a 65 mA base is of less interest than a 1mA change on a 7 mA base. In some applications this may give a clearer indication of a possible growing problem.

Finally, it is worth noting that some failure modes can be sudden, from nominally 'good' to failed in a few hours; we have several cases of such rapid onset situations where a likely catastrophic failure was avoided. In such cases we may not have time to see much development in the trends, but we can generate alerts for the current, phase angles, and instantaneous power factor and capacitances. In fact, we add an alert based on sending out the top-level alert immediately if any monitored value exceeds a preset limit.

Figure 6: Smoothed Power factor values for a single bushing

Adding Voltage Reference

If we add a voltage reference to a bushing monitoring system, we can now look at each phase individually as a 'true' power factor between a measured voltage applied and leakage current resulting; we no longer have to assume the 120° difference between phases. A previous article in Transformer Tech Magazine looked at the benefits of the dual relative and true approaches (5), noting that the 'true' power factor is, in practice, addressing the insulation of both the bushing and the source of the voltage measurement, usually a voltage transformer (VT); consequently, the approach is also monitoring the VTs but we would be uncertain as regards which is deteriorating. Relative and true power factor measurements are independent but complementary techniques: if a bushing is identified as deteriorating through relative power factor and true power factor measurements, we have strong evidence that it is the bushing which is in question, and the variation is unlikely to be an artefact of the system voltage variation.

A significant advantage of the dual relative and true power factors approach is that more than one bushing can deteriorate at any one time and we would be able to detect and diagnose that state.

Photo: ABB

Is this what you were expecting?

The following cases illustrate the need to set expectations. Over 95% of the time you do get what you expect, but the remaining may be somewhat challenging in terms of interpretation and diagnostics; in challenging cases engineering expertise is often needed to fully investigate and come to a conclusion.

Case 1: as expected

In Figure 7, on the left, we can see three phase angles for a power transformer, with a sudden change over a few hours of the angles related to the phase 2 bushing. On the right in Figure 7 we can see the variation in leakage current, with a sudden increase in current magnitude for the tap 2 (phase 2) simultaneous with the change in phase angles.

Figure 7 shows what we would hope to see in phase angles and currents in a system which is operating normally, as expected, and then 'sees' a sudden change in one bushing. This data was used to generate an alert and the bushing 'saved'.

Figure 7 shows what we would hope to see in phase angles and currents in a system which is operating normally, as expected, and then 'sees' a sudden change in one bushing. This data was used to generate an alert and the bushing 'saved'.

Case 2: not quite as expected

In Figure 8 we can see some interesting variations in the relative phase values for a set of low voltage bushings: none of the traces show a roughly constant value, and the rise in the blue trace is not a mirror in the fall of the orange trace. At the same time, the leakage currents were consistent both over time for individual traces, and relatively between traces.

The cause of the variation in Figure 8 is two bushings beginning to deteriorate – which is unusual.

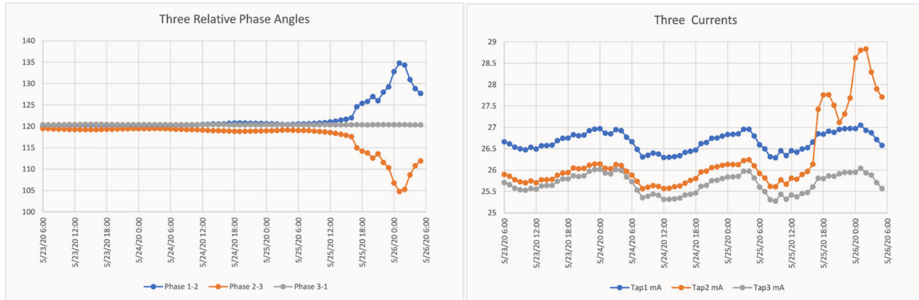

Figure 7: Sudden changes in phase angles and current magnitudes

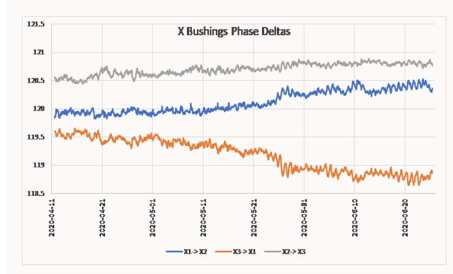

Figure 8: Variations in LV bushing relative phase angles

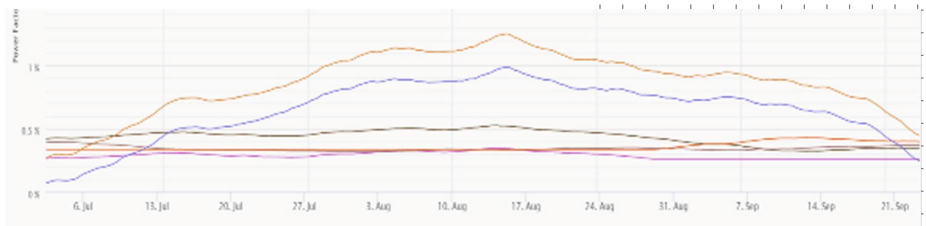

Figure 9: Relative and Trues Power Factor for 6 Tertiary bushings

One of the bushings has a power factor which has risen to almost 2.5%, the other to over 1%. The combination of effects gives the results in Figure 8.

The cause of the variation in Figure 8 is two bushings beginning to deteriorate - which is unusual. One of the bushings has a power factor which has risen to almost 2.5%, the other to over 1%.

Case 3: definitely not as expected

It's expected that we would be able to track the deterioration of a bushing which has an increasing power factor, and plan for offline testing and possible replacement. However, what happens if the bushing data indicates that the bushing is no longer deteriorating but 'getting better'?

Figure 9 shows such a case, where a set of three 23 kV tertiary bushings has both relative and true power factor shown (1).

It is very unlikely that a real bushing would 'get better', but can we come up with a scenario where the power factor decreases? There are several cases in the literature which discuss how reduction in power factor may occur, leading, in some cases, to negative values (3, 4).

In the case here a scenario was identified which could explain the effect – an oil fill gasket at the top of the bushing could leak, allowing ingress of moisture, which would, initially, cause deterioration of oil quality and a rise in power factor. Over time, a consequent build-up of contaminants on the surface of the bushing conductor would build up a resistive path to ground and allow the power factor of the bushing to decrease. A subsequent offline test confirmed the online results.

Discussion & Conclusions

To get the best from your bushing monitor, it is vital to set expectations up at the outset and ensure the monitor, its maintenance and management are included in the asset management plans of the organization. Then we can expect to get sensible data which can be used to both detect bushing deterioration and subsequently support bushing investigation and diagnostics.

It is important to identify not only expectations, but also what may be considered normal and acceptable for a particular application: then we can set alerts for anomalous data which may indicate a deteriorating bushing. Both identifying normal/acceptable and subsequent investigation may need detailed engineering expertise.

To realize the value of condition monitoring in general, and for bushings in particular, it is important to understand failure modes which may apply, their timescales, and the need for written and agreed response plans: what to do, who should do it, by when and with what feedback.

Acknowledgement

The author would like to thank his many colleagues who provided discussion of practical aspects of bushing monitoring.

References

[1] "The Asset Management Context: Condition Monitoring..." J. Beardsall et al, EEA Conference 2023, Christchurch, New Zealand

[2] "Intelligent Condition Monitoring", T. McGrail, Doble Life of a Transformer Seminar, 2020, Orlando, USA

[3] "Negative Power Factor of Doble Insulation Test Specimens (An Analysis)", D. Kopaczynski, S.J. Manifase, 55th International Conference of Doble Clients, Boston, USA, 1987

[4] "Review of Negative Power Factor Test Results And Case Study Analysis", L. Pong, 70th International Conference of Doble Clients, Boston, USA, 2002 Pong

[5] "Power Factor: Offline Relative and True", Transformer Technology Magazine, Summer 2020, Issue 6

Photo: Shutterstock