ABSTRACT

When dealing with transformer diagnostics, it's important to follow the ABC approach: Assume nothing, Believe nobody and Check everything. Through a couple of case scenarios, this article presents how the ABC approach was successfully applied to transformer diagnostics and how the following the ABC approach can prevent wasted time and effort and ensure accurate results.

KEYWORDS:

ABC approach, contamination, DGA analysis, diagnostic, insulation, methodology, power factor

Tony McGRAIL

The ABC approach encourages us to Assume nothing, Believe nobody, and Check everything, which can help avoid unexpected consequences and ensure accuracy in our work.

Transformer diagnostics: Easy as ABC?

If, for whatever reason, you're running tests on a transformer or gathering operational and condition data to try and diagnose its true condition, it is quite unlikely that the transformer is trying to deceive you. It may just seem that way during an investigation: inconsistent results, anomalous measurement values, unexpected data. However, we can apply some 'procedures' from the world of crime detectives to support our diagnostic efforts and, hopefully, find out the reality of the transformer condition. Admittedly detectives may be up against people who are definitely trying to deceive them, so for our transformer analyses, we apply a slightly 'softer' version. The cases given here are all factual – if you have an interest in the fine detail, please email us, and we can go deeper.

Check your ABCs

I first came across the ABC approach in a crime novel [1] and have seen it appear in different forms in other works since then; its origin may be lost to time, but the core is: "Assume nothing, believe nobody, check everything". A version we can apply would be a little less draconian, seeing as we don't think the transformer is actively working against us:

Assume nothing:

- Are you sure that the DGA sample really has no acetylene?
- Was the sample taken correctly?
- Are you sure the test leads are securely in place?
- Does deteriorating insulation only ever show a rising power factor (tan delta, loss angle)?
- Good experiences may mean we assume the test set is reliable – but we need to check it is
- Do you even know what assumptions are being made in generating the data and results?

Believe nobody:

- Maybe we can tend to believe people with a history of being right or factual
- Do we have health and safety issues all under control? Barriers? Risk analyses? Grounds?
- Does the team really know how to use the test set? Or do they 'Google search' know?
- Has there been a software change?
- Is this oil sample taken from the right location? Not just which valve, but which transformer?
- Is the history you're getting accurate? Or is it more like gossip? Where's the data?

Check everything:

- Check assumptions – both explicit and tacit assumptions can be misleading
- Check connections, grounds, and safety procedures – then check again

It didn't take long to realise that it wasn't the samples or the test instruments which were the cause, but a red flashing light indicating 'Test in Progress' within the room, which generated significant PD itself

- Check the stories you're being told – trust but verify
- Check the monitoring data – does it make sense? Does it meet expectations?
- Check with people who know what they're doing.

The cases given here are really just tales of the unexpected: detailed checking helping to avert disaster; incorrect assumptions made with painful results; checks not performed, leading to wasted time and effort. A little more thought and application of ABC could, or did, make things easier.

Case 1: Assumption made regarding a test fixture

A test laboratory set up a new shielded room in order to test devices and insulation samples for Partial Discharge (PD). When first put into service, samples were found to have higher levels of PD when tested *inside* the shielded room than when tested outside of the room. It didn't take long to realise that it wasn't the samples or the test instruments which were the cause, but a red flashing light indicating 'Test in Progress' within the room, which generated significant PD itself. After the light was disabled, the stray PD disappeared. You might think someone would have checked the light before installing it, but no – someone assumed that it would be OK, and it clearly wasn't!

Case 2: Check results and check again

When a power transformer trips out of service due to a fault, there is a lot of work to be done to find out the nature of the fault and whether the transformer is in a condition to be returned to service. Such was the subject of a compelling paper by Mike Wolf [2], where an essential transformer on a site undergoing a lot of improvement work tripped out. The fault was identified as being inside the transformer differential zone. With a lot of pressure to return the transformer to service, oil samples were taken for DGA analysis by a portable IR analyser, with the results indicating low levels of fault gases and no acetylene. Operational pressure to return the unit to service only increased in light of the results, but Mike was suspicious of the readings as although they were at acceptable levels, and they didn't look consistent with previous results; he insisted on lab samples being taken and rushed to the Doble labs for analysis. Two samples were taken, and both revealed high levels of acetylene, indicating the fault occurred within the transformer. If the initial portable DGA analyser results had been assumed correct, the transformer would likely have been returned to service with catastrophic results. It was Mike's engineering skills and the decision not to just blindly believe the portable device which averted disaster.

Case 3: Power factor rise and fall – can we assume the bushing got better?

When insulation deteriorates, it usually does so with an increasing power factor. However, a falling power factor is also possible and can indicate some serious contamination within the insulation [3]. When monitoring three transmission transformer tertiary bushings using a combination of relative power factor (RPF) and true power factor (TPF) [4], both values increased for one bushing over several weeks, then decreased, returning to their initial levels. No other

Several scenarios were considered which could explain the results, but the only one which made sense was that it was a result of a possible leaking gasket at the oil fill cap at the top of the bushing, allowing moisture into the bushing

Figure 1. Rising and falling RPF and TPF

bushings in the set or on the transformer showed a similar effect, as per Figure 1.

Should the bushing be left in service? Has it healed itself? Several scenarios were considered which could explain the results, but the only one which made sense with respect to the bushing construction and initial deterioration was a result of a possible leaking gasket at the oil fill cap at the top of the bushing, allowing moisture into the bushing. The initial moisture ingress could affect the oil first, raising its power factor, then internal resistive tracking follows as moisture and contamination build-up on internal surfaces, leading to a reduction in power factor. Out-of-service tests were performed, which confirmed the online results, and the bushing oil fill cap gasket was found to be cracked.

When I opened both clips simultaneously, I received a hand-to-hand shock of some magnitude as I'd broken the shorting link but had inserted myself into the circuit

Just because the measurement seems to show the bushing has 'healed' doesn't mean that the bushing has, in fact, 'healed'. If left in service, the bushing would have undoubtedly failed.

Case 4: Safety first – assumptions incorrect

On-site at a generator station, testing of a 400 kV 660 MVA step-up transformer, of three single-phase units was performed as part of a regular condition assessment program. During a winding resistance test of the high-side windings, it was noted that one phase took a little longer to 'settle down' than the other two phases. After the test, the HV windings were discharged, grounded, and a safety light came on to indicate the test leads could be disconnected, which was then done. At that point, we went to make connec-

The interpretation was that the individuals performing the test weren't familiar with the expected results and assumed the variations meant a possible problem with the transformer

tions on the LV side, and the phase with a longer settling time was found to still have the shorting leads across the terminals from a previous test. This would have caused the longer settling time on the HV measurement, following Lenz's law, and we should have thought through the consequences a little more deeply at that point.

We needed to remove the shorting lead before performing the LV winding resistance, but I was worried that, somehow, there might still be a voltage present on the windings as they were shorted but not grounded. I took some time to think it through and 'backhanded' the shorting leads at the point where two alligator clips were joined to see if any voltage was present. Nothing. I then somewhat gingerly took hold of a test clip, with no ill effect, and then took hold of another clip attached to the first. No voltages noted.

When I opened both clips simultaneously, I received a hand-to-hand shock of some magnitude as I'd broken the shorting link but had inserted myself into the circuit. I wasn't too badly affected, but it did make me think: How did this happen? After a few minutes, I'd worked out the physics to a reasonable degree of certainty, explaining both the slow winding resistance measurement and the subsequent shock through the original test setting up a circulating current in the LV windings, which had not dissipated: and a low resistance winding would mean that any voltage present would be very low. When I notified the safety team of the incident, I was told "That's impossible." It was only when a practical mock-up of the situation showed how a current could be induced and then maintained in the shorted LV winding that they were convinced. My assumption that no voltage meant no danger was incorrect.

Case 5: SFRA studies – Part 1 – what do those traces mean?

Recently I received a set of Sweep Frequency Response Analysis (SFRA) traces and asked to comment on them – what would they signify? Now SFRA is not a difficult measurement to make, but the interpretation is more complex as we are looking across a frequency range and interpreting a picture. OK – I used to call it 'squiggle theory', but those are some extremely useful squiggles, allowing detection and diagnosis of a range of problems, from core issues to shorted turns,

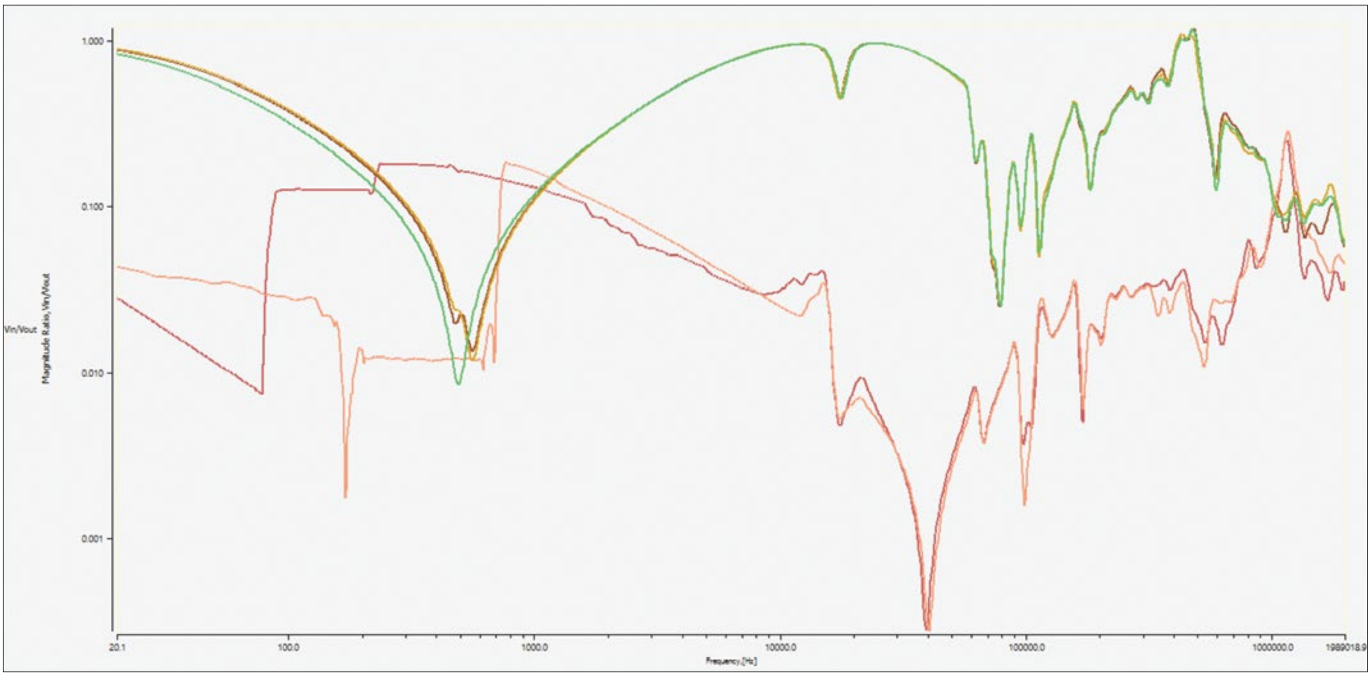


Figure 2. LV open circuit SFRA traces

to winding damage. Looking at the Low side open circuit results in Figure 1, the traces show good correspondence and the expected low-frequency form. No previous SFRA results were available, but nothing in the traces indicated any significant issue. Similar correspondence and form were measured for the HV open circuit.

The next time the SFRA tests were performed, the results had some improvement; the demagnetisation process was repeated several more times until the expected results appeared

However, there are serious variations between traces in the HV Short circuit, as in Figure 2. One phase looks as expected, but two have sudden changes in direction, which would be difficult to associate with a physical object within the transformer, which could provide such sharp inductive / capacitive response changes.

But if you've seen it before, it makes sense! What we're seeing is the effect of loose shorting leads on the LVs when measuring the HV short circuit respons-

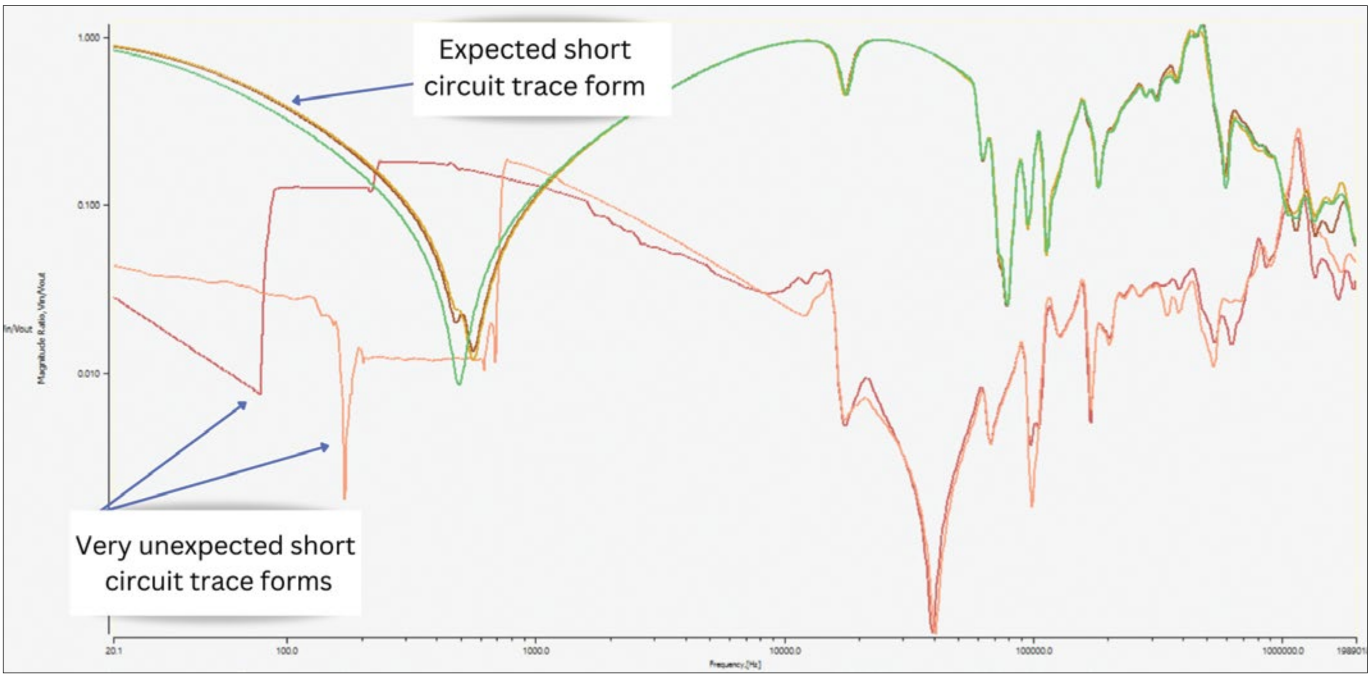


Figure 3. HV short circuit results

Sometimes we have to check what should have been done previously, just in case, as here, the transformer was not in the expected state

es: the traces, at low frequencies for the inductive roll-off area, are between the expected results for open circuit and short circuit measurements. The interpretation was that the individuals performing the test weren't familiar with the expected results and assumed the variations meant a possible problem with the transformer. They know better now.

Case 6: SFRA Studies – Part 2 –did you demagnetise the core? Yes!

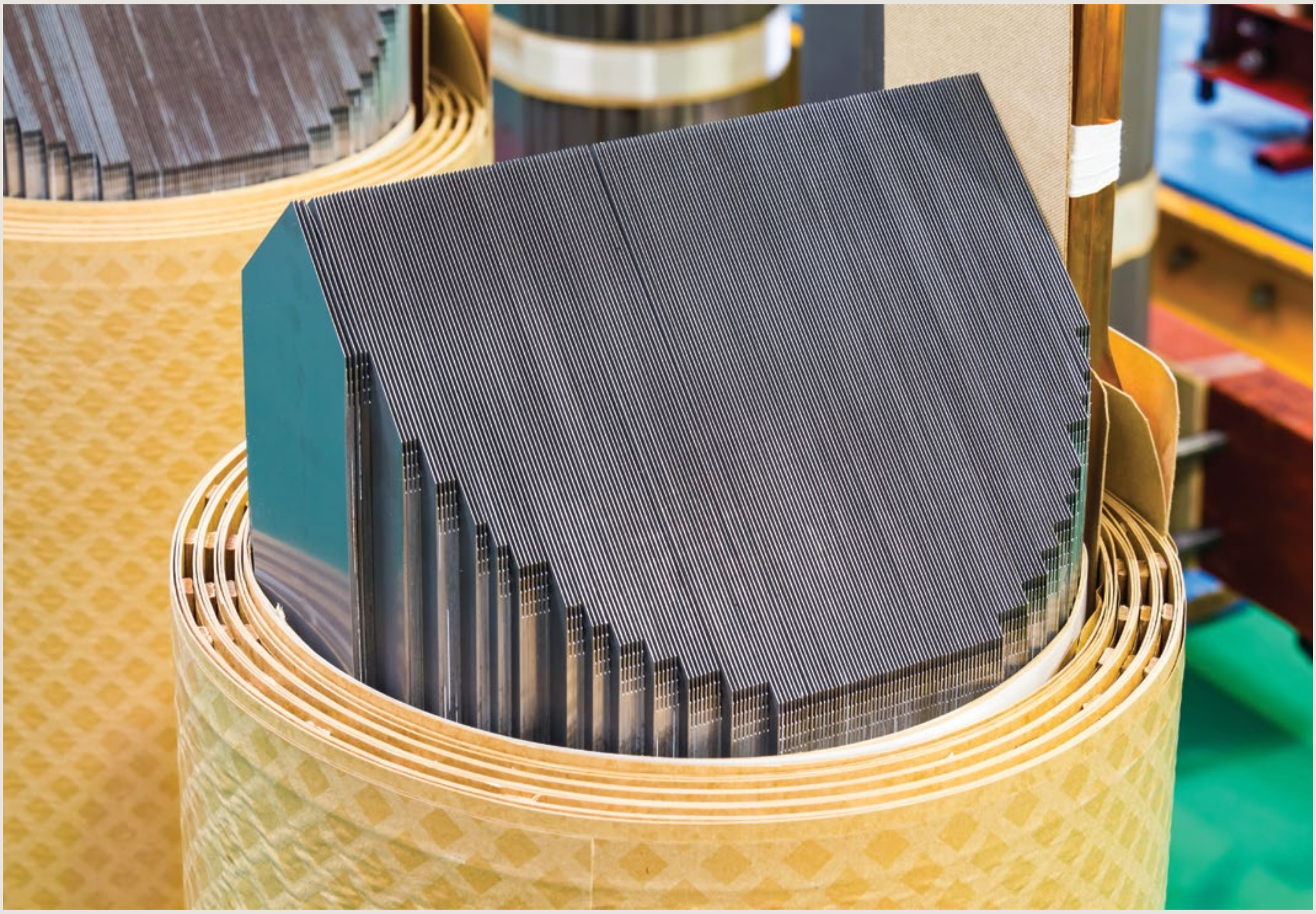
Factory SFRA testing is often performed as part of the manufacturing process to ensure the quality of the coils; it is also common to take measurements pre-shipping the transformer as a baseline for reference should anything untoward happen in transit. In this case, the factory test SFRA pre-shipping results did not look acceptable at low frequencies, indicating possible core issues. Other tests did not indicate a problem, but repeated efforts with SFRA, including tests across and between windings, clearly indicated a possible problem.

One way in which the low-frequency response can be affected is if the core is magnetised. An obvious question: did you demagnetise the core? The answer was 'yes', using the winding resistance test set – there was even a light which came on to show that the core demagnetisation had finished. Next question: 'can we try it again?' The answer was yes, and the demagnetisation process repeated. The next time the SFRA tests were performed, the results had some improvement; the demagnetisation process was repeated several more times until the expected results appeared.

The assumption that the demagnetisation process was complete was a poor one, even though a demagnetisation procedure had been followed and the light came on to indicate completion. We learned to check sooner rather than spend time looking for other possible causes.

Case 7: SFRA & LR – which to trust?

A transmission transformer on an international tie-line had a bushing failure. Subsequently, the bushing was replaced, and the transformer was tested using all available methods to give confidence that it could be successfully returned to service: power factor, capacitance, winding resistances across all taps, excitation, turns ratio, SFRA and Leakage Reactance (LR) and more. Everything showed good results and indicated 'no problem' except LR, which indicated one bad phase. The use of SFRA and LR is a powerful combination to identify possible winding movement and/or deformation, but finding inconsistent results was a surprise. Both tests were



repeated multiple times in multiple ways with the same results: SFRA shows no significant capacitive / inductive changes, and LR shows significant changes from baseline, with the tertiary winding seemingly the root cause. With the pressure on to get the unit back in service, a difficult decision had to be taken – we may have to go inside the transformer to do a repeat visual inspection: with all the time, effort and money involved.

Almost in desperation, I asked to check the CTs on all windings – the unit had been successfully commissioned many years prior, and they should all be complete, as per said commissioning tests. As it happens, the CTs had been left the open circuit on the tertiary winding leading to a burden which had little effect on the very low voltage low current SFRA but was significant for the much higher current LR. The CTs were connected up, the transformer retested, the LR and SFRA results now all looked good, and the transformer was successfully returned to service.

Sometimes we have to check what should have been done previously, just in case, as here, the transformer was not in the expected state. Don't assume it was done right.

It was a Sherlock Holmes tale which featured the line: "Eliminate the impossible, and whatever remains, however improbable, must be the truth

Discussion

Applying the ABC helps identify where we might have significant problems in our diagnostic process, but I'd actually like to add one more letter to the ABC sequence: a D for don't jump to conclusions, so maybe an ABC(D). It was a Sherlock Holmes tale which featured the line: "Eliminate the impossible, and whatever remains, however improbable, must be the truth. [5]" The problem is: can we identify all the things which may be 'impossible' without having assumptions and multiple checks in place? Are there things we haven't even thought of eliminating? And if we do come to a conclusion quickly, are we prepared to ditch that conclusion should the data so indicate?

Don't jump to conclusions:

- Have theories or scenarios which seem to explain the data, but don't draw conclusions on limited data! "Insensibly, one twists facts to suit theories instead of theories to suit facts. [5]"
- New data may mean you have to reconsider previous data, which is fine if you're prepared to let the initial theoretical conclusion go… but many people like to stick with first impressions, which may lead to bad decisions
- Just gathering data to confirm a theory, or a conclusion, may support the theory but doesn't prove it true; you can only prove a theory wrong [6] (unless it's a purely mathematical theory, in

A little scepticism goes a long way, and following the ABC (and D-don't jump to conclusions) for diagnostics can reduce wasted time, effort and occasional pain

which case it may not relate well to reality anyway…)

- The only true test of your theory is to gather more data which challenge the theory: and if the data doesn't support the theory, then it doesn't matter how cute or clever the theory is. It's just wrong [7]. The rejected theory may be a useful step towards a more correct theory

Discussion: in closing

It was physicist Richard Feynman who gave us the quotation, "The first principle is that you must not fool yourself, and you are the easiest person to fool [8]." The implication being that a little scepticism goes a long way, and following the ABC(D) for diagnostics can reduce wasted time, effort and occasional pain.

Assume nothing
Believe nobody
Check everything
Don't jump to conslusions

Acknowledgement

With thanks to colleagues in the industry who have provided thoughts on this article, especially **Ken Elkinson** and **Fernando Leal**.

Bibliography

[1] B. Aaronovitch, *Moon Over Soho*, 2011

[2] M. Wolf, *A 50 MVA Transformer Failure as Experienced by Maintenance Engineers*, 79th International Conference of Doble Clients, 2012

[3] T. McGrail et al., *Condition Monitoring to Detect Insulation Deterioration in Bushings and Power Transformers*, Electrical Insulation Conference (Insucon) UK, 2023

[4] *Bushing Power factor: Offline, Relative and True*, Transformer Technology Magazine, Summer 2020, ISSN 2642-2689

[5] A. Conan-Doyle, *The Case Book of Sherlock Holmes*, 1927

[6] www.forbes.com/sites/startswithabang/2017/11/22/scientific-proof-is-a-myth/

[7] blogs.scientificamerican.com/guest-blog/the-key-to-science-and-life-is-being-wrong/

[8] podcasts.apple.com/us/podcast/the-easiest-person-to-fool/id1028908750?i=1000507359305

Author

Dr. Tony McGrail is the Doble Engineering Solutions Director for Asset Management and Monitoring Technology. He has several years of experience as a utility substation technical specialist in the UK, focusing on power transformer tests and assessments, and as a T&D substation asset manager in the USA, focusing on system reliability and performance. Tony is a Fellow of the IET and a Member of IEEE, CIGRE, IAM and ASTM. He has a degree in Physics with a subsequent PhD in Applications of AI to Insulation Assessment.