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Photo: Vaisala

Detection of air leaks with total gas pressure

by **Senja Leivo**

Ambient air is the sole source of oxygen in transformers... Modern power transformers usually have sealed designs, and older ones are often upgraded with sealing systems to keep out oxygen and moisture, extending their lifespan.

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Why aging of the insulation system matters?

Transformers that employ cellulose based solid insulation are typically expected to function for decades under their nominal load and specified ambient temperature conditions. The aging of a transformer is influenced by its design, materials, contaminants within the insulation system, and operational conditions. The combination of water, oxygen, and acids within the solid insulation speeds up the aging process and degrades cellulose molecules, resulting in diminished mechanical strength and a consequently shorter lifespan for the transformer.

Under normal operating temperature in a water and oxygen free environment, ageing processes are almost nonexistent. However, making a transformer completely free of oxygen and moisture is not practical or affordable. It's been reported that if the oxygen level in the oil stays below 2000 ppm, the insulation system ages more than five times slower than in a free breathing transformer. It's important to know that aging isn't limited to cellulose; the insulation oil also undergoes aging, mainly through oxidation, which forms carboxylic acids that can speed up paper aging.

Ambient air – the sole source of oxygen and moisture

Ambient air is the sole source of oxygen in transformers. Simultaneously, the primary supply for water is atmosphere, where humidity levels consistently exceed those found within transformers. To tackle this, transformers use preservation systems like a rubber bag or nitrogen blanketing, creating a protective barrier between the insulation oil and the surrounding environment. Modern power transformers usually have sealed designs, and older ones are often upgraded with sealing systems to keep out oxygen and moisture, extending their lifespan. Air leaks, usually caused by gasket or rubber bag deterioration, have become a significant concern, especially when transformers operate at higher loads. The increasing use of sealed designs makes it crucial for asset managers to ensure that the transformer tanks remain airtight, requiring simple and straightforward methods to confirm their tightness.

Identifying the limits of traditional methods

Leaking happens over time and creates varying rates of air ingress. Traditionally, finding air leaks involved measuring oxygen and nitrogen in standard DGA oil samples. However, the risk of sample contamination with outside air has been a major challenge. When samples are taken at the transformer site, transported, and handled, they can pick up oxygen, leading to wrong data interpretation.

Online measurement of oxygen concentration in oil is a way to confirm air entry, but it won't detect slow air leaks when active oxidation processes are simultaneously consuming oxygen. Additionally, interpreting oxygen measurements requires an experienced DGA specialist. Even after more than six decades of using dissolved gas analysis in the industry, there is still no recognized standard or established common practice for interpretation of oxygen concentration.

Some DGA monitors include integrated oxygen measurement, and nitrogen levels are calculated based on those values. However, these calculations assume constant oxygen-nitrogen ratios in air-saturated oil, making them unsuitable in that respect for sealed transformers.

What really matters for asset maintenance teams?

Aging of insulation system is not just about what happens in the paper; it also involves the liquid. To understand the aging process, one can't rely solely on gas concentrations like O_2, CO_2, and CO. It's crucial to also consider oil quality parameters, such as acidity, and ageing markers like furans or methanol. Assessing the remaining life of solid insulation is a complex task that demands a higher level of expertise. Unlike transformer faults that may develop rapidly, oxidation is a slow process, usually taking years to show significant progress. Therefore, real-time gas monitoring isn't necessary for tracking oxidation, as it is for quickly evolving faults.

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Ultimately, decision-makers in transformer maintenance do not need to know precise oxygen or nitrogen concentrations. What matters most is to know whether the insulation system of a sealed transformer is exposed to air, the source of oxygen. Based on that information, they can plan for repair of the sealing system, oil degassing or dry out and so forth.

Finding the solution – a step forward in air leak detection

A simpler way to spot air entry is by measuring the pressure of all gases dissolved in oil. Total gas pressure (TGP), which sums up the partial pressures of all these gases, is an uncomplicated and easy-to-understand parameter.

Once the gases are extracted by the DGA monitor, their pressure can be measured. The key fault gases—hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide, and carbon dioxide—make up only a tiny fraction of the pressure where nitrogen and oxygen are dominant factors. Increase in TGP in a sealed transformer signals an air leak, without the need for specialized opinions or interpretations.

For new transformers, the pressure of dissolved gases should be very low due to degassing of oil during commissioning. In a sealed transformer, the pressure stays low. However, a noticeable increase in pressure indicates a potential issue. Even when oxygen sensors can't catch slow air leaks due to oxygen-consuming reactions, the TGP value remains reliable. This is because the proportion of nitrogen dominates and increases over time, as it is neither formed nor consumed in the transformer.

Seal leaks aren't a simple yes or no situation—they develop gradually, leading to different rates of air entry over time. By measuring the pressure of dissolved gases, utilities can easily spot the entry of air if the TGP rises. A properly sealed transformer should maintain low gas pressure levels for its entire lifespan, well below atmospheric pressure 1000 hPa (14.5 psia). If the TGP value starts to rise, it's a clear sign that air is making its way in. This suggests an issue with the transformer's sealing system, whether it's related to materials or workmanship—especially if the increase follows maintenance work. If the data indicates a recent ingress of air marked by an increase in total gas pressure, maintenance teams can decide whether they need to inspect and repair the sealing system during the next service break. This ensures there's no further deterioration of the insulating paper due to oxygen.

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TGP measurement in practice

Properly membrane-sealed transformers in service typically have a pressure of dissolved gases ranging between 100 to 300 hPa (1.45-4.4 psia). Figure 1 illustrates the TGP measured using the Vaisala OPT100 online DGA monitor. It also displays as reference calculated partial pressures of oxygen and nitrogen at 50°C, based on gas concentrations determined by a laboratory from standard DGA oil samples with gas chromatography. The data is from a new transmission transformer with membrane sealing, with monitoring initiated a few weeks after the transformer commissioning.

Over 11 months, there was a 23 hPa (0.33 psi) increase in TGP, having respective increase in nitrogen (N_2) 1500 ppm and none detected in oxygen (O_2) in oil. The clear increase in nitrogen concentration without oxygen indicates an active ageing process consuming oxygen probably occurring. This highlights the sensitivity of pressure measurement to even minor air ingress. Additionally, the TGP measurement is inherently free from air contamination, a constant risk when using oil samples.

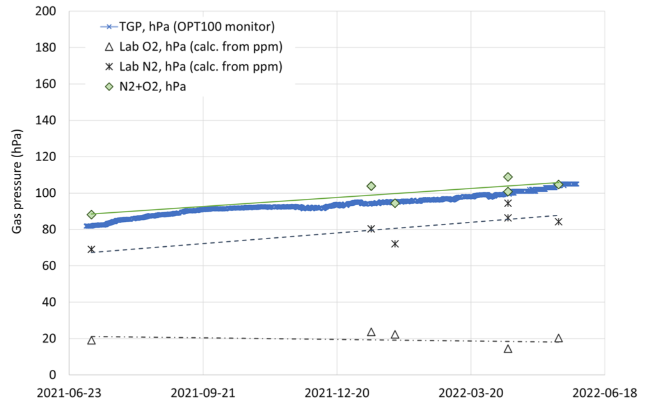

Figure 1
Total gas pressure (TGP) and calculated partial pressures of oxygen and nitrogen at 50°C with linear fitting.

Figure 2 presents real-time TGP readings measured from two sealed generation step-up (GSU) transformers. GSU1 maintains a consistently low TGP level in its initial two years. Right after commissioning, there's a release of gases into the oil due to air from the transportation phase, present in the oil-impregnated paper. This gradually moves to the bulk oil, causing a slight increase in TGP, which then stabilizes at a low level. The average annual increase in TGP after stabilization is only 7 hPa (0.1 psi), suggesting it would take with the same rate around 130 years to reach equilibrium with atmospheric pressure. In the real transformer application, achieving complete gas-tightness without any minimal air ingress through diffusion is not possible. However, the data indicates that GSU1 is well-sealed and doesn't require any actions in this respect.

The TGP data for sealed GSU2 after degassing presents a different scenario. Following degassing, there's a quick 30 hPa (0.43 psi) increase due to gas coming from the oil-impregnated paper. Unlike GSU1, this increase doesn't stabilize; instead, there's a steady rise at a significantly higher rate. Over the next two years, the rate of change is approximately 60 hPa/year (0.87 psi/a). If this rate continues, it will take roughly 15 years the oil to become saturated with air. It's apparent that more oxygen, and possibly moisture, is entering the transformer continuously, potentially reducing its lifetime. At this point, it becomes important to weigh the expected lifespan of the transformer against the costs of investigating and repairing the leakage or implementing other mitigation actions. Due to the nuanced nature of these decisions, it may not always be practical or economically relevant to attempt fixing the leakage.

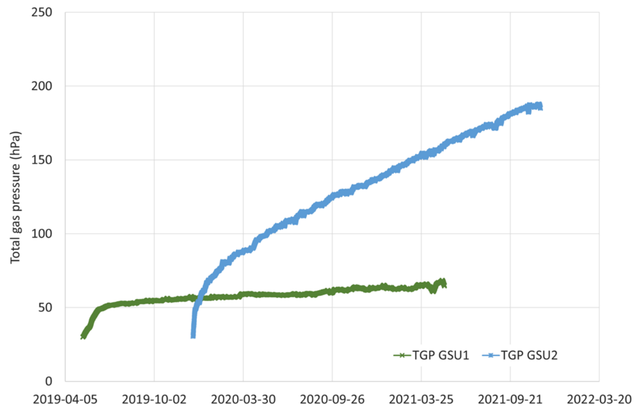

Figure 2
TGP data of two new power transformers right after transformer commissioning.

O_2/N_2 ratio, is it important?
IEEE standard C57.104-2019 includes O_2/N_2 ratios in its gas concentration tables (90th and 95th percentile), which are often called as typical values of fault gases. Does this imply a need to start calculating these ratios? No, it doesn't. The ratios were solely introduced to differentiate between different transformer designs in the database of 1.5 million DGA results, where the transformer design information was not available. To select relevant reference values for DGA data of a transformer, one only needs to know the design of their transformer in question. Sealed and nitrogen blanketed transformers fall under the column with O_2/N_2 ratio <0.2, while free-breathing transformers fall under >0.2.

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