Dielectric Liquid – A Key to Reliability and Predictive Maintenance

by **Jason Dennison**

When considering the reliable life of transformers, dielectric liquids serve as critical indicators of operational integrity to mitigate risk of failure. The significance of these liquids lies in their ability to provide insights into the current condition of the transformer. Expanding on the foundation laid out in last year's article "Insulating Liquids: The Lifeblood of Transformer Reliability", this article endeavors to delve into further technical context for using liquid analysis as a crucial component of reliability and predictive maintenance.

Predictive Maintenance: A Superior Approach to Transformer Reliability

The choice between predictive and reactive maintenance significantly impacts the reliability and operational longevity of transformers. Reactive maintenance operates on a simple principle: wait for a component to fail, then repair or replace it. While this has strength in simplicity, it carries substantial risks when applied to the reliability of transformers. When a transformer fails unexpectedly, it can lead to extensive downtime, costly repairs, and catastrophic system failures.

The safety implications to personnel of unplanned power loss, coupled with the financial implications of unplanned downtime, and potential collateral damage to other equipment make reactive maintenance risky as a maintenance strategy.

Predictive maintenance is a strategy to leverage operational knowledge, data collection, and data analysis to monitor the condition of the transformer to provide insight into its condition and trends in the available data to inform decisions to take action to prevent unplanned downtime and sudden system interruptions.

Performing analytical testing on the dielectric liquid has proven to be an effective and cost-effective method to monitor and detect changes within the transformer that can indicate when maintenance may be performed to prevent outage and extend the reliable life of the transformer. The superiority of predictive maintenance is not just its ability to preemptively identify potential faults, but also in its capacity to optimize maintenance activities and schedules to keep costs as low as possible and minimize impacts to operations. To fully realize the benefit, it is imperative to build an understanding of what can be learned from the common dielectric liquid tests.

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Research and tests

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Understanding Transformer Health through Liquid Testing

A crucial aspect of predictive maintenance lies in the meticulous analysis of dielectric liquids. There are several common tests that can provide insight into a transformer's condition, enabling reliability and maintenance engineers to make informed decisions regarding operational health and potential maintenance requirements. While the specific results for indicating health of a transformer depend on factors such as dielectric liquid type, transformer size, and transformer voltage class, having a general understanding of the tests and what the results may indicate can expedite maintenance decisions and improve maintenance and reliability outcomes. In all cases, it is important to note that trends over time are essential in helping to understand the health of a transformer. In the US, laboratories generally follow testing procedures defined and governed by ASTM International, while result interpretation comes from other sources including IEEE (The Institute of Electrical and Electronics Engineers) and practical experience. Below, the most common tests will be introduced; there are additional tests that can be performed to gain even deeper insight into transformer health not included here.

Oil Quality "Liquid Screening" Tests

Many tests are generically termed "oil quality" or "liquid screening" tests, which characterize the dielectric liquid's physical properties, indicate evidence of premature aging of the solid or liquid insulation in the transformer, and identify presence of contamination.

Acid Number ASTM D974
This test measures acid content in the dielectric liquid. Acids will form due to liquid and solid insulation oxidation. A higher acid number suggests degradation has occurred, potentially leading to the breakdown of solid insulation. In-service dielectric liquid should have a low acid number if the transformer is healthy.

Interfacial Tension (IFT) ASTM D971
Interfacial tension is a measure of the liquid's integrity, by determining the force required to break the interfacial tension between the liquid and water. This tension force diminishes if contaminants or degradation byproducts, particularly polar compounds, are present in the liquid. In-service dielectric liquid should have a higher IFT measurement if the transformer is healthy. In many cases, IFT has an inverse relationship with Acid Number – as acids increase, the IFT will decrease.

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Color Number ASTM D6045/D1500
The color of the dielectric liquid provides visual cues about its condition, though this test alone is not a sufficient analytical tool. Darker liquid can indicate of aging of the insulation, oxidation, or the presence of impurities. This test is often used to corroborate other test results that may indicate premature aging or other fault conditions. In-service dielectric liquid should generally have a low color number, though a higher color number is not necessarily indicative of poor health.

Specific Gravity ASTM D1298
Specific Gravity is a fundamental physical property of the dielectric liquid, related to its density. Major changes to specific gravity suggest the liquid is contaminated. In-service dielectric liquid should maintain a reasonably consistent specific gravity.

Visual & Sediment ASTM D1524
Visual inspection, although seemingly rudimentary, is an important part of liquid screening. Specialists assess the oil's clarity, looking for signs of sediment, carbon particles, or water droplets. Any visual anomalies observed during the inspection can guide further diagnostic interpretation, aiding in the identification of underlying issues. In-service dielectric liquid should be free of particulates, sediment, or observable water droplets.

Dielectric Testing ASTM D877, ASTM D1816

Dielectric liquid testing, as per ASTM standards D877 and D1816, plays a vital role in predictive maintenance. These tests evaluate the oil's breakdown voltage, indicating the dielectric strength of the liquid, which can indicate issues such as contamination, insulation degradation, and in some cases may also highlight elevated moisture content. The D877 dielectric test, which uses flat electrodes submerged in dielectric liquid, was the primary test for breakdown voltage for years. For many years now however, the D1816 dielectric test has grown in adoption as the best dielectric test as it uses rounded electrodes (called "VDE") in dielectric liquid that better approximate conditions inside the transformer related to breakdown voltage and dielectric performance. D1816 is notably more sensitive than D877, and care must be made to get a representative sample. In the diagnosis of results, the presence of elevated dissolved gases and moisture are known to affect D1816 testing, and maintenance decisions based on dielectric results should be made respective of other test data. In-service dielectric liquids in healthy transformers should have high breakdown voltage results.

Karl Fisher Moisture Analysis ASTM D1533

The presence of moisture in transformers is problematic for both the liquid and solid insulation. Moisture in the liquid can increase the risk of dielectric failure. In the solid insulation, when combined with heat, moisture will expedite the aging of the solid insulation and begin to create acids that will harm the integrity of the solid insulation. Moreover, moisture is often a symptom of transformer component failures where seals or gaskets break down and create a path for moisture incursion.

Getting an accurate analysis of moisture content is therefore important and notably, moisture testing is highly dependent on sample accuracy. When sampling, it is crucial to only use approved containers and to fill the container fully to have the highest integrity sample possible. Resources such as ASTM D923 and ASTM D1533 include requirements and procedures to help ensure sampling is properly performed. It is critical at the time of sampling to accurately note the sample temperature as well - moisture is unique in that it will migrate between the liquid and solid insulation depending on temperature.

As temperature increases, some moisture will migrate from the solid insulation to the liquid insulation and will revert as temperature decreases. Recording sample temperature allows a laboratory to report the proper analysis for moisture which includes both the water content in parts-per-million (ppm) and a calculated Percent Saturation (%Sat). Percent Saturation expresses moisture content relative to how much moisture the dielectric liquid is able to hold, which is important to understand based on the significant impact temperature has on moisture content distribution inside the transformer.

The recommended in-service moisture levels depend heavily on liquid type and voltage class of the transformer. Generally, in-service dielectric liquids should have low moisture content, and more importantly, low percent saturation.

Photo: SDMyers

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The data collected has a direct link to the liquid and solid insulation condition, and the premature aging or degradation of either will have significant impact on the reliability of the transformer.

Dissolved Gas Analysis ASTM D3612

Dissolved Gas Analysis (DGA) is a cornerstone of predictive maintenance in transformers. By analyzing gases dissolved in dielectric liquids from transformers, experts can glean valuable insights into the internal condition of the transformer. Generally, dielectric liquids are tested for 9 gases - atmospheric gases (Oxygen, Nitrogen, Carbon Dioxide) and combustible gases (Carbon Monoxide, Methane, Hydrogen, Ethane, Ethylene, Acetylene) – that may be found in dielectric liquids inside transformers that can be used to determine abnormal conditions in the transformer.

Long term conditions and incipient faults can both be readily seen in DGA data, making it particularly useful in both predictive and reactive maintenance situations. The concentrations of individual gases, the rate of gas generation, and the overall gas profile in a transformer can be interpreted using practical expertise and diagnostic tools such as Duval Triangles, Duval Pentagons, the Key Gas Method, and parameters from standards organizations such as IEEE to determine possible fault conditions inside the transformer. These tools can be of great use in helping to quickly process available data.

However, the true power of DGA interpretation lies in the fusion of these diagnostic tools with practical experience and domain expertise. An experienced practitioner will bring contextual understanding to the analysis, considering factors such as the transformer's history, nameplate data, operational conditions, and environmental factors. Employing experience, reasoning, and diagnostic tools adds depth to DGA diagnostics, ensuring that maintenance decisions are informed by situational and operational dynamics.

It is difficult to generalize expected gas levels for in-service dielectric liquids. These liquids in normal use may exhibit some amount of some of the combustible gases and will likely have some level of atmospheric gases as well. The expected values also vary greatly with liquid type, transformer size, preservation system type, and operating conditions of a transformer. Generally, gas values should remain reasonably consistent over time in the absence of faults or component failures, so trending is important in establishing a useful diagnosis of the available data. Elevated levels of gases, especially the combustible gases, is likely cause for investigation.

Reliability is About More than Data Analysis

These tests represent the most common tests that can be performed on dielectric liquids inside transformers, though there are other tests that can provide insight into transformer health. Additional tests such as Liquid Power Factor, Inhibitor Content, Furanic Compounds, and Elemental Analysis can be performed to gain even deeper understanding of the condition of the transformer. In the pursuit of predictive maintenance, the data that is available from the dielectric liquid can provide incredible insight into the condition of the transformer. The data collected has a direct link to the liquid and solid insulation condition, and the premature aging or degradation of either will have significant impact on the reliability of the transformer. To extend the reliable life of a transformer, the maintenance approach must move beyond gathering and analyzing data to favor taking more proactive measures to correct deficiencies found in the data early, which has the greatest potential impact to reliability. Doing so can extend the reliable life of a transformer by years, if not decades.