



Insulating Liquids: The Lifeblood of Transformer Reliability

by **Jason Dennison**
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You may know that your transformer is filled with a liquid known as an insulating or dielectric liquid, but do you know why?

The very first transformers did not have an insulating liquid in them. Air acted as the dielectric medium inside early transformers and this became a problem as energy needs expanded, given the early designs of transformers. In early transformers, energy losses generated a significant amount of heat in the core and coils and the air wasn't effective at drawing away the heat. As a result, early

transformers' size was limited – otherwise the heat was simply too much, and the transformer would fail due to overheating.

Elihu Thomson patented the use of mineral oil as an insulating liquid in 1893 as a way to manage the heat and improve the operation of transformers, and within about five years this advancement was commercially available. The early intent was focused on dissipating heat while also dielectrically protecting the energized parts of the transformer, and mineral oil proved to be a very good medium for this.

If the transformer is the heart of the electric power system, the insulating liquid is the blood, and it can tell you an incredible amount of information about the transformer's condition.



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The Functions of Insulating Liquids

Fast forward several decades, and mineral oil became the de-facto insulating liquid in large transformers. For smaller applications, transformers that use air as the dielectric also became popular for many applications, commonly referred to as "dry type" transformers. Into the 1940s, vacuum-filling as a process opened further advancement in transformers' application and size. As larger, liquid

filled transformers grew in use, four primary functions of the insulating liquid became well-known:

1. Dielectric Strength
2. Heat Transfer
3. Protection of Solid Insulation
4. Diagnostics

These four functions are widely recognized and the liquid inside these transformers is crucial to the normal operation of transformers from generation to distribution.

These functions point to why these liquids are so crucial:

Dielectric Strength – The liquid insulates energized components inside the transformer, helping to ensure routine operation of the transformer. While the liquid is an insulator, there is another insulation medium in transformers – called the solid insulation. Solid insulation is comprised of paper and board that serve to insulate the winding. Interestingly, it is the combination of the solid and liquid insulation that is so profound due to a synergy between the two that yield a dielectric strength improvement of 20 – 25% greater than expected. The combination is greater than the sum of its parts!

Heat Transfer – Transformers, depending on size and load, can generate a significant amount of heat. The liquid helps dissipate that heat and enables transformer designers to use natural and generated convection to keep the transformer within operating parameters for temperature and load. Liquid properties such as viscosity, heat capacity, relative density, and the thermal expansion coefficient are all key properties affecting the liquid's performance in heat transfer.

Protection of Solid Insulation – Transformers contain solid insulation comprised of paper and board that lend strength to the transformer in normal operating conditions. This paper is susceptible to damaging effects of oxidation, and the liquid acts as a barrier between the solid insulation and "bad actors" that lead to oxidation such as oxygen, heat, and moisture.

Diagnostics – The liquid inside the transformer is analogous to the blood in our body, and just as a blood sample can tell the doctor about our health, the liquid can be tested to help evaluate the condition of the transformer. This was not part of the original intent of adding insulating liquid to transformers, yet it has become an incredibly useful aspect to help ensure the reliable operation of a transformer.

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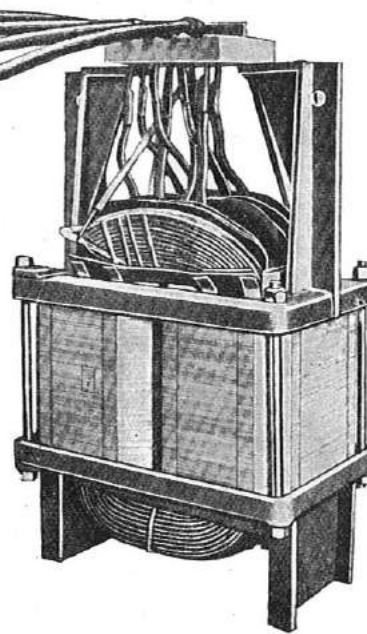
Liquid Types

In early transformers, the insulating liquid of choice was mineral oil, due to its dielectric strength and ability to handle heat generated in the transformer.

It was so common that to this day, the insulating liquid inside transformers is generically referred to as the "oil" inside the transformer, even though other liquids have been used for years as well. For a time, pure PCBs were used as an insulating liquid but due to environmental and health concerns, PCBs are now a rarity in transformers. Let's look at the common insulating liquids used in liquid-filled transformers:

Mineral Oils

Today, many transformers are still filled with naphthenic or paraffinic mineral oil, often called "transformer oil". This is a derivative of petroleum oil that is well-established as a



dielectric liquid, which has strong performance in terms of cooling and is known to have high dielectric strength. Due to its long history of use in this application, mineral oil characteristics are well-understood as they relate to performing diagnostics on the liquid. Mineral oils also perform well in applications difficult for other liquids such as load tap changers where arcing occurs in the insulating liquid, or in free-breathing

applications where exposure to oxygen causes polymerization of some liquids. Mineral insulating liquids generally have a price advantage compared to other liquids. Mineral oils are also readily processable and can be restored to near-new condition by hot oil cleaning processes.

Silicone Liquids

Silicone liquids are a synthetic oil that can be used as a dielectric liquid. Silicone has high dielectric strength, high flash and fire points, and is chemically inert. These characteristics have led to the use of silicone oil in indoor applications where flammability is a significant

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concern. Silicone also has a slow oxidation rate in the presence of oxygen at elevated temperatures (>175°C); when oxidation does occur over time, it results in polymerization of the liquid, which is measurable by the viscosity of the liquid, but does not form harmful acids or sludges. Use of silicone oils in transformers has been decreasing over recent years, as arguably better performing and definitively more environmentally friendly liquids (natural and synthetic esters) have become available at lower prices.

Natural Esters

Natural esters are a type of environmentally friendly dielectric liquid that is readily biodegradable, derived from agricultural crops such as corn, rapeseed, soybean, and sunflower. While this is an advantage in itself related to spill containment and material handling, these liquids have some performance advantages compared to mineral oil as well. They typically have high flash and fire points, making them great for indoor applications where flammability is a concern. Esters also have a high capacity for moisture saturation, leading to claims that refilling an oil-filled transformer with a natural ester can aid in dehydrating the solid insulation. These esters polymerize when exposed to oxygen, typically have higher viscosity than mineral oils, and are not as readily processable for restoration to near-new condition. Natural esters are compatible with mineral oils, making retrofills feasible when service is needed. There are also synthetic ester liquids available with similar characteristics but improved low-temperature performance and formulated to prevent oxidation if exposed to air, as in free-breathing applications.

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The Heart of Power System Reliability

If the transformer is the heart of the electric power system, the insulating liquid is the blood, and it can tell you an incredible amount of information about the transformer's condition. Liquid sampling and testing is cost-effective and highly informative, and the liquids also play a key role in other diagnostics such as infrared (IR) thermography and continuous monitoring devices.

Typical Tests

The most common tests are indicators of general aging and contamination, moisture incursion, and incipient faults. It is imperative that the sample pulled is representative, and methods exist to help define the sampling process such as ASTM D923. Once you have a good sample, there are many tests available. Typical tests are:

- **Liquid Screen** – A group of tests that looks for signs of premature aging of the dielectric liquid. A liquid screen can also point to contamination from internal issues such as coking or sludge, or external issues such as contamination from other liquids.
- **Karl Fischer** – This test measures the amount of moisture in the dielectric liquid, and the liquid

temperature can be used to calculate the percent saturation of water. This is an important test because elevated moisture results in accelerated aging of the solid insulation and if high enough can even result if the failure of the transformer. Moisture in dielectric liquids can also lead to oxidation and formation of acids that degrade the solid insulation.

- **Dissolved Gas Analysis (DGA)** – DGA detects the presence of key gases that can identify incipient faults from low- to high-energy events and can point towards issues with the solid insulation.
- **Power Factor** – This test can indicate liquid breakdown, contamination, and in some cases, moisture.
- **Inhibitor** – Transformer oil typically includes an inhibitor to help prevent oxidation, which can lead to premature aging of the liquid; this test quantifies the amount of inhibitor in the liquid.
- **Furan Analysis** – A byproduct of paper degradation is the formation of certain compounds, called furans, which can be quantified and correlated to the state of aging of the solid insulation in the transformer.
- **Metals in Oil** – This test can determine very low quantities of dissolved metals such as aluminum, copper, and iron.



Infrared Scanning / Thermography

Liquid-filled transformers also provide an opportunity to use infrared scanning to look for signs of thermal issues in your transformer. Infrared scanning, or thermography, can identify anomalies such as overloading, unbalanced loads, low liquid levels, issues with the cooling system, hot spots, loose connections, and faulty gauges. While thermography can be used on any electrical asset for thermal profiling, the insulating liquid helps highlight issues such as hot spots, liquid level, or other cooling issues due to the heat transfer properties of the liquid.

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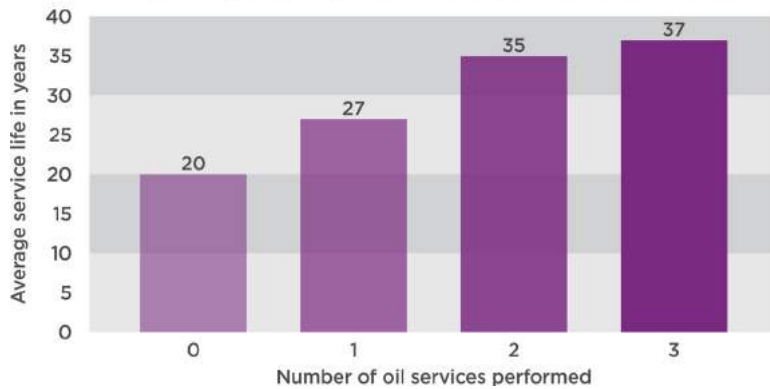
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The data shows that insulating oil maintenance results in about six years of additional service life each time it is performed!



Average Service Life Related to Number of Oil Services Performed

An SDMyers study based on 1,534 decommissioned oil-filled transformers > 500 kVA



Liquid Monitoring

Another benefit of the insulating liquid is that technology advances in the past several years have created the opportunity to monitor some health characteristics in addition to laboratory testing. Monitoring devices are readily available that can monitor moisture levels and dissolved gas (DGA) levels, which have long been only available by laboratory testing.

These devices often offer additional data collection as well, such as liquid temperature or even load on the transformer to aid in diagnostics. The ability to closely watch trends in these important insulating liquid related values is a significant step in ensuring the reliable life of a liquid-filled transformer.

Ensuring the Reliable Life of your Transformer

The insulating liquid in your transformer is at an intersection where its use is ubiquitous and the potential to learn about the health of the transformer is enormous. It is crucial to the reliability of your transformer, so it should be a priority to keep in excellent condition and correct any deficiencies quickly. The data shows that insulating oil maintenance (oil reclamation, moisture reduction, or re-inhibit) results in about six years of additional service life each time it is performed! Keeping the transformer in good condition via routine and responsive maintenance and maintaining the insulating liquid are sure-fire ways to help ensure the reliability of your electrical power system and extend the useful life of your critical power assets.

