Best Practices for Online Oil Maintenance in Transformer Assets

by **Steve W. Leath**

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Economic Environment Affecting Utility Maintenance

Today's energy utility industry is experiencing a high-water mark in terms of pressure to reduce Operating and Expense (O&M) expenditures. This pressure extends to the maintenance of generation, transmission, and distribution assets, and the trend shows no sign of waning. The direct result of this financial environment is that utility corporations of all sizes are becoming increasingly creative in reducing O&M spending. Maintenance intervals are being extended and, in some cases, assets are no longer maintained and are therefore classified as "run-to-failure." Assets that may be considered as "run-to-failure" include power transformers below a designated kVA rating and single-phase voltage regulators.

Adopting these more limited maintenance strategies is accompanied by accepting more risk of unplanned equipment outages and premature failures; consequently, it is critical to mitigate as many of these risks as possible. Many utilities accomplish this by making capital investments in online condition monitoring equipment and online filtration of insulating oil, among other approaches. This discussion will focus on continuous online filtration strategies for transformer assets.

History of Oil Filtration for Substation Assets

Online oil filtration has been recognized as a best practice in the industry for nearly three decades, beginning with the filtration of insulating oil in load tap changers during the early 1990s. This then expanded to voltage regulators and oil circuit breakers, all with the objective of eliminating harmful carbon particulate produced during the normal "arcing in oil" functionality of these assets. One large US utility conducted a 20-year study (1995-2015) on load tap changer (LTC) maintenance expenditures and authenticated a 72% reduction in maintenance costs per asset over the 20-year period.
This was accomplished by requiring a comprehensive filtration strategy and adopting a condition-triggered maintenance program. Today, increasing numbers of utilities are adopting online filtration programs for power transformers and vacuum LTCs in order to obtain and maintain acceptable moisture levels in the insulating oil.

Photo by Steve W. Leath

Filtration Basics

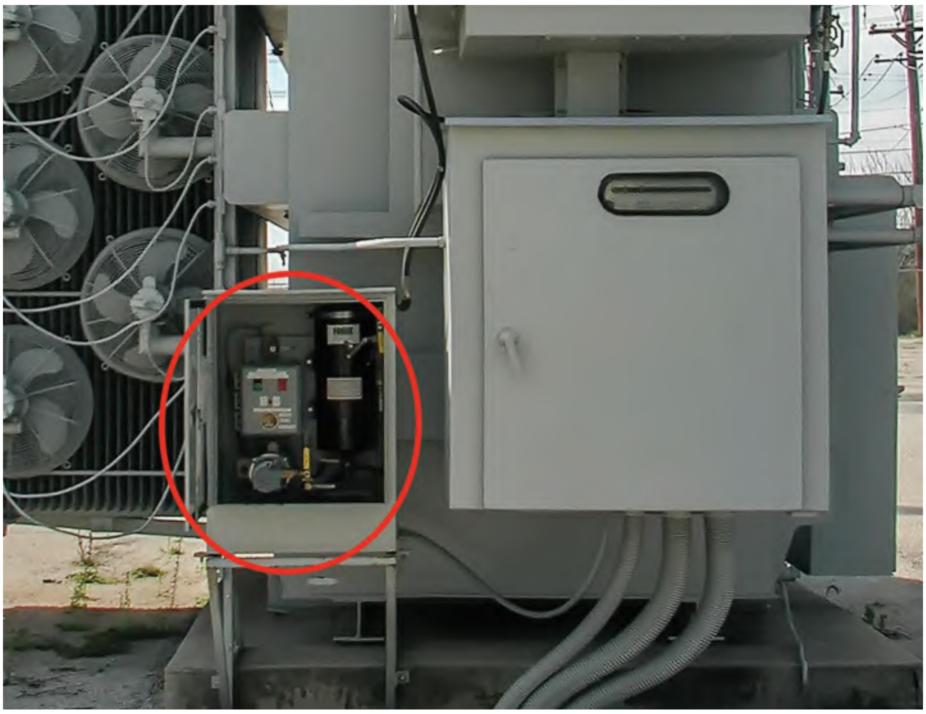
Oil filtration in general is performed in the interest of removing contaminates. The contamination typically of most concern in insulating oil is particulate, free water, and dissolved water. It is also possible to improve the chemical properties of oil, such as acidity content, by using appropriate filter media. Filtration and conditioning can be performed either offline while the equipment is out of service, or continuously online while the equipment is in service. This discussion will focus on continuous online filtration applications. To understand filtration capabilities, it is necessary to understand the types of filtration media. There are many media types and this discussion will cover only those most relevant to the utility industry. They are as follows:

There is a long history of utilizing online filtration for load tap changers (LTCs), and this practice has proven to significantly reduce required maintenance and associated O&M resources. Oil filtration in LTCs can eliminate time-based maintenance and extend the frequency of oil sampling.

Depth Wound Cellulose Media:
This media utilizes a specifically designed paper as the means of removing contamination. These filter elements contain thousands of square feet of cellulose which makes them extremely effective at removing particulate and free water. These filters can also remove a nominal amount of dissolved water. You can envision this filter media as a very high-tech paper towel made from coffee filters. This element is the ideal method for any device that breaks electrical current in oil, such as LTCs.

Molecular Sieve Media:
This media utilizes a molecular sieve material which is extremely effective at removing dissolved water. It contains microscopic pores ideally sized for capturing water molecules suspended in oil. This is the ideal filter type for removing dissolved water from insulating oil and is the filter of choice for dehydration of transformers. The oil is easily dehydrated to a level that will then remove water from the cellulose insulation, which is critical to the longevity of the asset.

Pleated Hybrid Media:
This media utilizes a pleated cellulose barrier for particulate and a polymer for water removal. The cellulose barrier contains only a fraction of the surface area of a depth wound filter but can remove particulate, and the polymer is very effective at free water and dissolved water removal. This filter type performs well with higher flow rates, the initial removal of water, and applications where multiple contamination types are present.



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Online Filtration of Load Tap Changer Oil

As mentioned earlier, there is a long history of utilizing online filtration for load tap changers (LTCs), and this practice has proven to significantly reduce required maintenance and consequent associated O&M resources. Oil filtration in LTCs can eliminate time-based maintenance and extend the frequency of oil sampling. Since LTCs are an integral component to many transformers, this is a major element of the transformer maintenance discussion.

Many modern LTCs utilize vacuum technology to interrupt electrical load current during the switching sequence. Bypass switches are necessary to accomplish the required routing of the electrical current through the vacuum interrupters;

these switches are very sensitive to oil conditions where the dielectric strength is compromised. The most likely scenario adversely effecting oil dielectric strength is dissolved water accumulation in the oil. When the oil dielectric strength becomes degraded, abnormal arc intensity across the bypass switches can occur which may result in dissolved gas generation not typical in a vacuum LTC. For this reason, in addition to maintaining proper insulating capacity in general, managing dissolved water content should be considered an important maintenance strategy. Maintaining very low moisture-in-oil content (less than 5 PPM) can easily be accomplished with online filtration and molecular sieve filter media.

While vacuum interrupting technology is common in the modern transformer LTC world, there are still tens of thousands of LTCs in service that interrupt the switching current in the insulating oil media. There are scores of these "arcing-in-oil" designs and all of them benefit from continuous online filtration. When the electric current is interrupted and the subsequent arc is extinguished in the oil environment, byproducts of this process appear. These include generation of dissolved gases and the production of carbon particulate which then becomes suspended in the oil. These particles compromise the dielectric strength of the oil like dissolved water, but also contaminate the switch contacts in the LTC switching components.

As these switch contacts become contaminated, film development on the contact surfaces causes an increase in the electrical resistance across the switches. This increased resistance creates excessive heating in the contacts which accelerates until there is formation of coke (burnt carbon) on the switches. This causes extreme dissolved gas levels in the LTC oil and, if not addressed with proper maintenance, the intense resistance and heating can burn the switching contacts open, resulting in a catastrophic event. This can all be mitigated with online filtration of the oil using depth wound cellulose filter media.

The following case study illustrates the benefits of carbon management in an arcing-in-oil LTCs.

Case Study Background
The study involved two transformers identical in design and both equipped with McGraw 550B load tap changers. The transformers were operated in parallel and each LTC performed over 20,000 switching operations annually. For the purposes of the study, each transformer was removed from service and the LTCs were thoroughly serviced. After the inspection and service, each LTC was retro-filled with new oil. On Bank No. 1, a filtration system was installed on the LTC and equipped with a Depth Wound Cellulose filter media. The LTC on Bank No. 2 was without filtration. The transformers were placed in service for six months and then again removed from service to be inspected. Bank No. 1 LTC (filtered) had performed 12,434 operations since the service, and Bank No. 2 LTC (non-filtered) had performed 12,289 operations. The inspection findings were summarized as follows:

- Bank No. 1 LTC (filtered): The oil was clear and bright and the lab analysis indicated that the fluid qualities were still at new oil specifications. There was also a reduction in acid level which was positive in terms of oxidation potential. The switch contacts were free of filming and carbon accumulation (Figure 1).
- Bank No. 2 LTC (unfiltered): The oil was nearly black from carbon accumulation. The lab analysis indicated an increase of acid level, indication the early stages of oxidation. The contacts had significant filming (Figure 2).

A primary consideration regarding the life expectancy of a transformer is the proper maintenance of water content in both insulation systems, namely the oil insulation in the main tank and the cellulose winding insulation.

Figure 1. Bank No. 1 LTC (filtered) after 12,434 operations

Figure 2. Bank No. 2 LTC (unfiltered) after 12,289 operations

Moisture concentrations will achieve equilibrium over time. By dehydrating the transformer oil, it will also effectively dehydrate the cellulose insulation in concert. Both aspects are key to maximizing the transformer life.

Photo by Steve W. Leath

Online Filtration of Transformer Main Tank Oil

A primary consideration regarding the life expectancy of a transformer is the proper maintenance of water content in both insulation systems, namely the oil insulation in the main tank and the cellulose winding insulation. Elevated water content has adverse effects on both insulation systems, and it is important to understand the implications. IEEE offers specific guidelines on the water content in both insulation systems.

Regarding oil insulation, the primary measures of water content are concentration in parts per million (ppm), and relative saturation as a percentage (%) of the amount of water in the oil compared to the amount of water it can hold at a given temperature. For example, oil at 40°C will hold about 120 ppm of water. If the actual water content is 12 ppm, the relative saturation is 10%. Maintaining acceptable dielectric strength is the critical concern, and the dielectric strength of the oil is more proportional to the relative saturation than the concentration. Therefore, relative saturation is the ideal measure in understanding the dielectric strength of transformer insulating oil. IEEE provides limits on maximum saturation for oil filled equipment based on primary voltage class. For transformers, the limits are as follows:

- Up to and including 69 kV – Not to exceed 15%
- Above 69 kV and less than 230 kV – Not to exceed 8%
- 230 kV or greater – Not to exceed 5%

It is important to note that reaching saturation levels of 5% or less are generally achievable with continuous filtration using molecular sieve filter media. Some considerations include oil volume and leakage rate of the transformer.

Regarding cellulose insulation in a transformer, the key measure is percent moisture by dry weight. Accelerated aging on the insulation system is a primary concern with elevated moisture in cellulose insulation. Moisture by dry weight in cellulose is generally determined by the relative saturation of the oil. Water concentrations in both systems will become equalized over time and temperature conditions. Water content in the cellulose decreases both the electrical and mechanical strength of the insulation, and in severe cases can cause catastrophic failure due to bubble evolution in the transformer insulation. IEEE also provides guidelines for acceptable moisture by dry weight and these are correlated with the oil relative saturation limits defined above.

The key point is that moisture concentrations will achieve equilibrium over time. By dehydrating the transformer oil, it will also effectively dehydrate the cellulose insulation in concert. Both aspects are key to maximizing the transformer asset life.

The following case study illustrates the benefits of moisture management in power transformers.

Case Study Background

This case study involved a 300 MVA autotransformer with a primary voltage of 345 kV and a secondary voltage of 138 kV. An online filtration system was installed and molecular sieve filter media was utilized. The transformer contained an oil volume of approximately 18,000 gallons and the initial oil conditions were 61 ppm and 39% relative saturation based on the incorporated moisture in oil sensor included with the system. This represented approximately a 4% moisture by dry weight in the cellulose insulation. In a one-week timeframe, the water in oil content was reduced to 10 ppm and 10% relative saturation. Over the next six months with continued filtration and filter changes, the water content of 5% relative saturation in oil was achieved. It is important to note that this saturation needs to be maintained over time to effectively dehydrate the cellulose.

Conclusion

It is critical to mitigate the risks associated with reduced maintenance programs driven by the current economic environment of the power utility industry. Online filtration offers a legitimate opportunity to alleviate some of these risks and migrate to a maintenance strategy that is more intelligent and condition-driven, rather than purely extending maintenance intervals.