Apart from fulfilling the primary functions of insulation and cooling, the oil serves as an important carrier of information

ABSTRACT

As blood tests provide information about a person's state of health, oil analyses provide information about the condition of a transformer. Transformer oil testing has proven to be an excellent tool for early defect identification in preventive maintenance of oil-filled transformers. It has permitted extended service life by giving a measure of both oil and solid insulation condition, and by identifying the presence of incipient thermal and dielectric faults. When performed regularly, oil analysis will help the asset manager run a cost-effective maintenance program for transformers.
This column addresses some recent developments in oil analysis, such as sustainable alternatives for mineral oil, an alternative marker for analysis of paper degradation, and online transformer oil monitoring.

KEYWORDS

oil analysis, ester, cellulose paper, degree of polymerization

The diagnostic power of oil analysis for power transformers: New developments

1. Introduction

Over the last decades a large variety of oil analyses techniques have been developed and standardized. These techniques involve physical or chemical oil properties, electrical and environmental properties, and DGA (Dissolved Gas Analysis). The application of oil analysis may be linked to maintenance, lifetime extension, and establishing the status of ageing and corrosion for replacement and refurbishment issues [1]. In the majority of oil-filled transformers mineral oil is used, and physical oil samples are taken in service for analysis in the laboratory. This column addresses some recent developments in oil analysis. The first one is related to sustainable alternatives for mineral oil, in particular esters.

The second one deals with methanol as an alternative marker for analysis of paper degradation, and the third one with the benefits and drawbacks of online transformer oil monitoring.

2. Natural esters as an alternative for mineral oil

From the start, mineral oils have formed the insulation and cooling medium of liquid-filled transformers. For most applications, mineral oil is a proven, acceptable, cost-effective insulating and cooling fluid. It has good thermal and dielectric properties, and there is a lot of experience gained over the years.

In recent years, manufacturers have introduced transformers with biodegradable liquids, in particular synthetic and natural esters. The advantages are primarily related to safety properties (thermal stability, flashpoint, smoke generation) and environmental properties (biodegradable). It is further claimed that they can absorb water without having a detrimental effect on dielectric properties, and that they have a longer life expectancy due to the reduced ageing rate of solid insulation. Transformers with such fluids are being introduced more and more, especially in applications where fire safety and environmental protection are important, and have reached a state of maturity. There is a trend to use them at ever increasing voltages and power ratings, and today there are examples of biodegradable fluids being used in high-voltage and high-power transformers.

Apart from fulfilling the primary functions of insulation and cooling, the oil serves as an important carrier of information. From physical and chemical analysis we assess whether the oil still meets the required specifications for continued use. With DGA (Dissolved Gas Analysis) dormant errors can be detected at an early stage. This gives us, as it were, a glimpse into the interior of the transformer without having to open it and even without having to take it out of operation. DGA is the most widely used technique worldwide for monitoring the operating status of transformers.

A drawback of changing from mineral oil to esters is that is has an impact on transformer monitoring and diagnosis. Most utilities have experience with mineral oil analysis as a standard diagnostic basis, and have built a history that serves as a reference for trending and analysis. For esters, the methods for assessing the condition can only be applied to a limited extent using IEC standards. IEC did issue a standard on new and unused natural esters, such as FR3. But so far there are no guidelines for esters in operating electrical equipment. New knowledge rules need to be applied, and a new history needs to be built up. IEC TC 10 is presently working on such a standard. It is to be expected that, in the longer run, a similar standard will be developed for the analysis of paper ageing through ester transformer oil.

3. Methanol as a marker for paper degradation

Transformer insulation paper is generally recognized as the most significant limiting factor in the thermal operating life of a transformer [2]. Not as much because it is the dominant failure mechanism – it is not, but because paper degradation is an irreversible mechanism that will eventually destroy the transformer and does (practically) not allow repair or refurbishment.

The winding insulation consists of oil impregnated cellulose. Cellulose has excellent electrical and mechanical properties, and interacts very well with mineral insulating oil. Under the combined effects of temperature, oxygen and moisture, the cellulose polymer chains will break up and result in a weak and brittle material that has lost its mechanical strength. Solid insulation in transformers not only serves as an insulator, but also ensures mechanical stability, creation of space, the proper direction of oil flow, and so on.

New insulating paper typically has a DP value between 1000 and 1200, which corresponds to a high tensile strength. As paper ages, its electrical properties do not change significantly, but the mechanical properties are reduced drastically. As a result, the mechanical strength of the paper is reduced with time, and when a DP value of about 200 to 300 is reached, the mechanical strength has gone. The rate at which the DP value decreases in time during service depends mainly on the temperature in the transformer, on the amount of moisture and oxygen present, and on the acidity of the oil. The main cellulose degradation process is acid hydrolysis, which requires water and acids. The process is accelerated by temperature, degradation byproducts and possible electrical fields. Figure 1 schematically illustrates the degradation process [3].

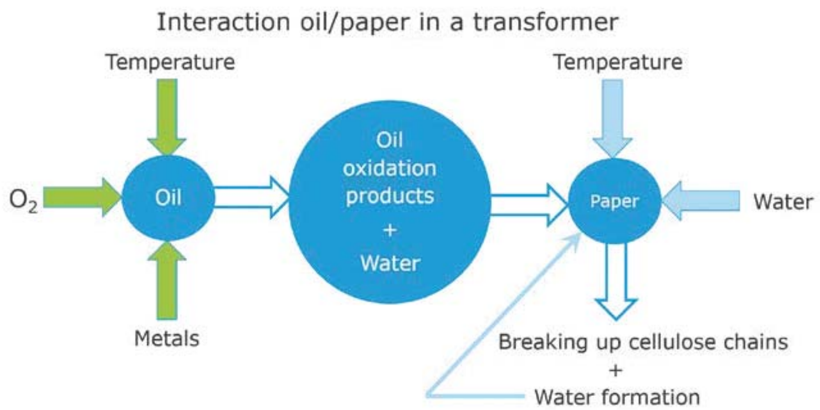

Figure 1. Schematic representation of the interaction between oil and paper

Oil testing gives a measure of both oil and solid insulation condition, and helps identify the presence of incipient thermal and dielectric faults

In the last decade, research has indicated that methanol is a promising alternative as a tracker for paper degradation

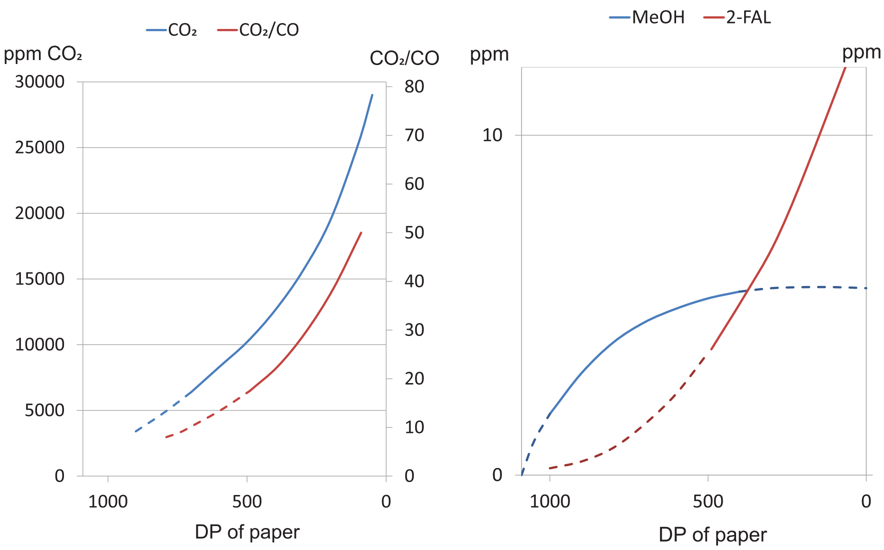

Figure 2. Typical correlations between DP value and marker concentrations/ratios [4]

For the above reasons, operators are keen to know the degree of polymerization (the DP value) of the insulation paper. Sampling paper for analysis is not a feasible option, not only because it requires opening the transformer, but more importantly, because the sample would have to be taken from the hot-spot location. The breakdown strength of the insulating paper is determined by the weakest link in the chain, which is the hotspot location. This is located inside the winding package close to the core.

Therefore, the DP value is determined indirectly from the byproducts in the oil that result from breaking up of the cellulose chains. The byproduct parameters used so far for assessing the DP value are the CO_2 concentration, the CO_2/CO ratio and the furfural content. In the last decade research has indicated that methanol (MeOH) is a promising alternative as a tracker for paper degradation [4, 5].

The assessment is based on the strong correlation between CO_2 concentration, the CO_2/CO ratio, the furfural content (2-FAL) and the MeOH content on the one side, and the DP value on the other [4]. This is illustrated in Figure 2.

The CO_2 and furfural concentrations are more sensitive to DP variations in the low DP range (below 400, late degradation stages), whereas the MeOH concentration is more sensitive to DP variations in the high DP range (above 400, earlier degradation stages). The methods may be regarded complementary. For early warning, the MeOH approach would be better, but close to the end of paper life, the furfural content may give a more accurate picture. It should be noted, however, that research is still ongoing to arrive at a reliable empirical relation between MeOH and DP value. At present, all three methods have some challenges based on their advantages and disadvantages. Table 1 gives an overview of the three methods discussed [3].

4. Online monitoring of transformer oil

For critical transformer units where premature or unexpected failure would have significant consequential costs one may consider to increase the oil sampling frequency for coping with defects that develop fast. This allows maintenance engineers to timely recognize incubating defects and take corrective action before they mature, however at the expense of cost, manpower and logistic complexity. It does, by its nature, not allow immediate feedback or alert.

These days, however, modern sensing and diagnostic equipment allows to replace sampling, transport and laboratory analysis of oil samples. Mobile on-site test methods are presently commercially available. By applying continuous on-line oil testing, in combination with intelligent electronic devices which can record and trend results and trigger alarms, we now have predictive diagnostic tools which can eliminate the risks associated with interval testing. On-line testing also eliminates the necessity of oil sampling and the associated issues related to contamination during sampling and storage. After all, the test results are only as reliable as the samples obtained. One might suggest that this will eventually lead to the end of sampled, interval-based, oil testing practice [7]. Will we exclusively use on-line predictive oil analysis in the future? To answer this question we need to understand the principles of both methods.

The **off-line analysis** provides a wealth of information from all kinds of analyses (physical and chemical properties and DGA), and needs to be performed on a regular basis. According to CIGRÉ [7], a typical maintenance interval for DGA, dependent on load, age and importance, varies from three months to two years. Once a defect is observed, the same sample may be used for additional analysis, and the sample frequency may be increased. Interpretation is performed by an expert (or a team of experts).

The **on-line analysis** is predominantly based on DGA monitoring, and ranges from simple fault detectors to full DGA monitoring systems, and may be performed continuously. The first interpretation can be made by knowledge rules embedded in software. In order to fully benefit from this feature it is important to ensure that oil is drawn from and returned to chosen points in the oil circulation circuit so as to ensure representative sampling. It is also important that the oil is suitably conditioned prior to testing to ensure measurement consistency. As mentioned earlier, on-line analysis may be used for fault detection or for a full DGA analysis.

Fault detectors usually operate on only one or two key parameters. As hydrogen is produced in all fault mechanisms,

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measuring dissolved hydrogen serves as an excellent fault indicator. Similarly, moisture is a very useful indicator of the overall condition of (and risks associated with) both oil and solid insulation. These are therefore regarded as key parameters. Fault detectors combined with intelligent logic systems allow to timely intervene in critical situations, but do not have the predictive power of a full analysis.

Complete DGA monitoring benefits from the DGA analysis advantages to the full. However, it does not monitor all physical and chemical properties, the costs rise with the number of key gases to be analysed, and complex situations still require an expert interpretation. The decision to use an on-line monitoring system involves a trade-off between the costs (costs of automated monitoring versus interval sampling and laboratory analysis) and the benefits (e.g. the failures prevented by timely detection). Expensive and strategic high-voltage transformers will have a better monitoring business case then medium-voltage commodities.

Also, one has to take into account that on-line systems need maintenance and calibration, and tend to have a lower accuracy then laboratory analysis.

Transformer oil testing is firmly entrenched in the condition-based maintenance practice. The results of oil analyses form an important part of the condition information feeding maintenance and replacement decisions. As such, oil analysis is increasingly integrated in decision support systems such as health and risk indexing software [8]. It is very likely that on-line monitoring will find its way on a limited scale, focusing on strategic applications. It is unlikely that on-line monitoring will replace off-line analysis at a significant scale in the foreseeable future, unless the parameters of the business case dramatically change.

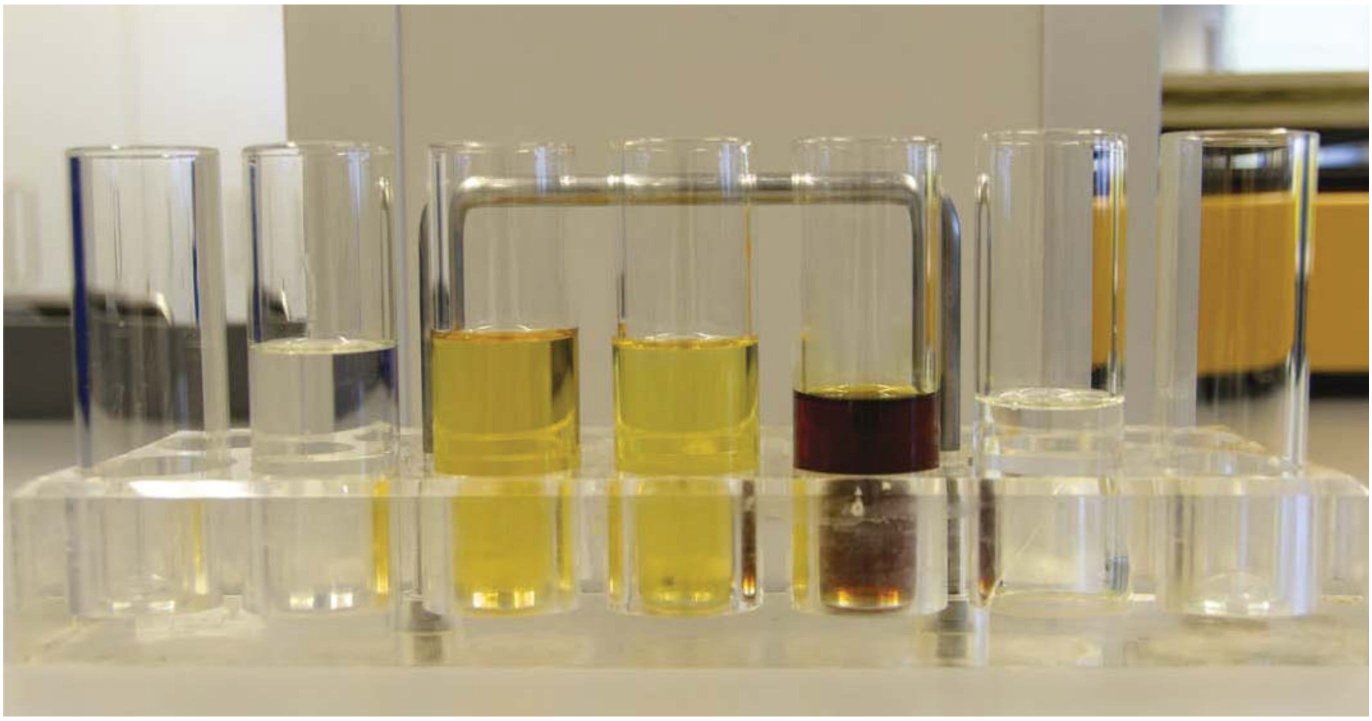
Conclusion

Transformer oil testing has proven to be an excellent tool for early defect identification in preventive maintenance of oil-filled transformers. It has permitted extended service life by giving a measure of both oil and solid insulation condition, and by identifying the presence of incipient thermal and dielectric faults. When performed regularly, oil analysis will help the asset manager run a cost-effective maintenance program for transformers.

New sustainable fluids are being developed as an alternative for mineral oils. Esters have become available with similar dielectric and thermal properties, but with superior safety and environmental properties. Further work is needed in order to develop guidelines for using ester analysis for diagnostic and maintenance applications.

Table 1. Overview of test methods for DP value determination (after [3])

Test	Advantages	Disadvantages	Challenges
CO_2 & CO	Laboratory or online test; Can be used as a flag to indicate cellulose ageing	Limited information on cellulose ageing; Origin can be solid insulation or oil; Gases may escape, depending on the breathing configuration	Difficult to determine source, location, type of degradation, degree of egress/ingress; May be dependent on manufacturer / design
2-FAL	Laboratory test; Estimates DP value; Empirical relation between 2-FAL and DP; Sensitive for late degradation (low DP)	Thermal instability furans; Detection limited at higher DP values	Proper interpretation requires knowledge on the insulation system
Methanol	Laboratory test; Estimates DP value; Empirical relation between MeOH and DP; Linear & sensitive for early degradation (high DP)	Requires knowledge on paper type, partitioning factors, size, design, breathing configuration	Establishing unit specific empiric equations still in development



For determining the ageing status of paper insulation, methanol analysis has been developed as an alternative for furfural analysis. It turns out that methanol has superior properties for identifying the early phases of paper degradation. However, further development is needed to arrive at empiric relations for interpretation.

It is anticipated that on-line oil analysis will increasingly be applied for high-value strategic transformers, but will not be able to replace laboratory oil analysis in the foreseeable future: for large numbers of medium-voltage commodities the benefits will not balance the costs.

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