TRANSFORMER'S MOISTURE ASSESSMENT WITH ONLINE MONITORING

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ABSTRACT

This paper discusses the application of online moisture monitoring of operating loaded transformers. Real-time monitoring offers many benefits the fleet operator can achieve that are discussed below and shown as data examples from operating transformers. The data collected in this paper also shows the varying moisture patterns of different transformers, proving them to be very individual depending on their loading and maintenance history. Water solubility of two aged oil samples was defined to illustrate the effect of oil ageing.

The many uncertainties related to the traditional method to define paper moisture from oil samples by applying moisture equilibrium charts are discussed on a general level.

INTRODUCTION

Power transformers are among the most valuable and important assets in electrical power networks. Knowing their condition is essential to meet the targets of maximizing the return on investment and lowering the total costs related to a transformer's lifetime operation.

Moisture is one dominant factor in solid insulation degradation. Traditionally moisture assessment of the insulation paper has been conducted from oil samples applying moisture equilibrium charts. However, this method includes many factors that may increase the assessment uncertainty significantly. There are various error sources related to the sampling and sample handling, which are discussed later in this paper.

It is also widely known that moisture in a transformer increases the risk of bubble formation and decreases the dielectric strength of insulation oil [1,2,3,4].

PAPER MOISTURE FROM OIL-SAMPLE

Moisture assessment of insulation paper of an operating transformer is commonly conducted from oil samples applying moisture equilibrium charts. Oil samples are taken from the transformer and sent to a laboratory to be analyzed for moisture with KF titration (coulometric). Such a method is susceptible to various factors that may affect the results.

The sampling procedure is crucial for reliable moisture results and thus should be performed with great care. Especially dry insulation oils are prone to contamination from ambient air moisture or moisture released from sampling system's materials in contact with oil. Even a small amount of water contamination can have a significant effect on final results.

The sample handling at a laboratory has to be performed with care. However, there is always some moisture ingress from atmosphere during the sample preparation. Therefore KF results tend to have a positive bias to higher moisture content especially with dry oil-samples. Also different reagents may give somewhat different results. Round robin tests have shown significant differences in results for identical samples. The results had a bigger variation with dry oil samples [5].

The fundamental drawback of the method based on oil samples is the long time constants to establish the equilibrium between oil and paper especially at lower temperatures [6]. This leads to a situation that the samples taken from transformers are often times not representative of equilibrium, because due to the load and temperature variations, equilibrium is hardly ever achieved in a loaded transformer (Figure 1).

MOISTURE DYNAMICS IN TRANSFORMER

Temperature fluctuation by load drives moisture exchange between oil and the solid insulation. At the temperature increase water is released from paper into oil and vice versa with the temperature decreasing [7,8]. The same moisture pattern is shown in Figure 1.

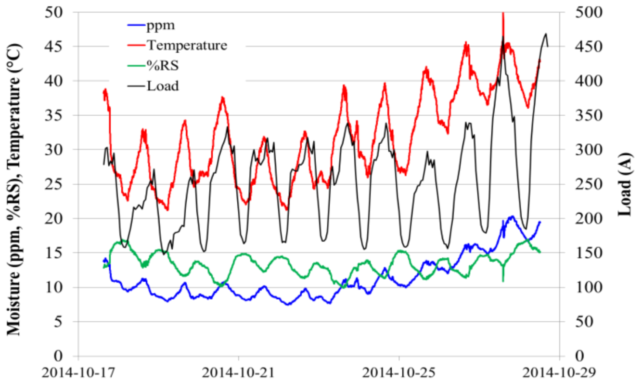

Figure 1 Online monitoring data: oil moisture, top oil temperature and load from a 30/60 MVA transformer (ON/OF).

Desorption is a faster process than absorption, indicated by hysteresis in online moisture data (Figure 2). Determining water content in paper is difficult with traditional sampling due to the hysteresis effect of the moisture migration between paper and oil. The moisture ppm results may vary significantly depending on where in the loading cycle the sample is taken.

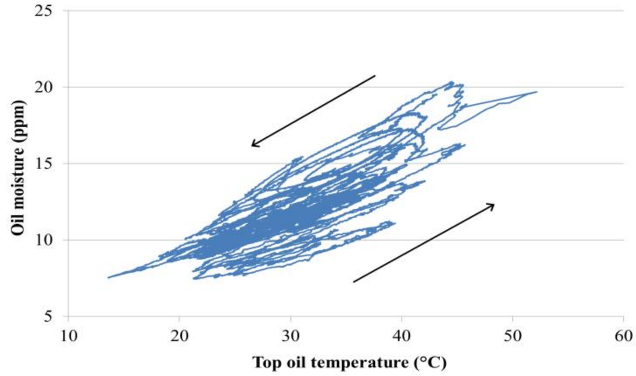

Figure 2 Online monitoring data from a 30/60 MVA transformer: oil moisture plotted as function of temperature

In a wet transformer the variation in oil moisture is clearly wider and thus the effect of sampling moment is even bigger. The data in Figure 3 shows that the moisture content of an oil sample taken at 35°C can vary between 30 ppm and 50 ppm depending on the previous loading history of the transformer before the oil sample was taken. If those values were used to define paper moisture using the Oommen's equilibrium curve the results would be 4.3% and 6% respectively. This clearly shows how misleading the results can be if moisture of solid insulation is defined only from an oil sample which is taken during the dynamic condition of a transformer.

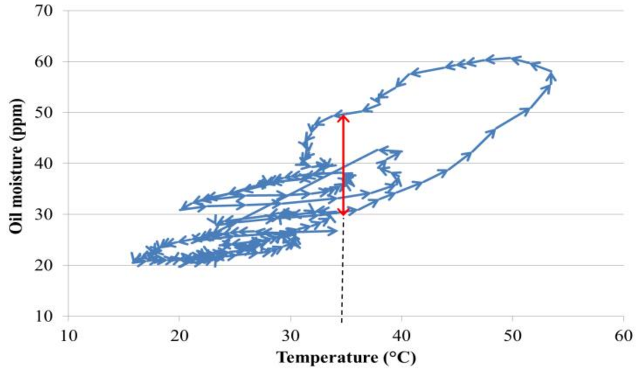

Figure 3 Online monitoring data from a 10 MVA transformer (ONAN): oil moisture (ppm) plotted as function of temperature (°C). Variation of moisture at 35°C is highlighted with a red arrowed line.

CAPACITIVE MOISTURE SENSOR

Capacitive sensors are used for online measurement of oil's relative moisture saturation (%RS) and temperature. Water activity is the driving force for moisture migration between oil and paper. In equilibrium relative saturation can be used as a reference for determining paper moisture. However, there is hardly ever equilibrium due to temperature fluctuations and the thermal mass of insulation. Also, relative saturation is a temperature dependent parameter and sensitive to the location of the sensor.

Water concentration in ppm can be calculated from relative saturation and temperature, when the water solubility characteristic of oil is known (Figure 1).

Structure of capacitive moisture sensor and its operating principle

A capacitive moisture sensor is basically a parallel plate capacitor. At least one of electrodes is porous to water and allows water to permeate inside the dielectric polymer layer. Absorbed water molecules increase permittivity and this can be measured as increased capacitance of the sensor element. The sensor is very selective to water and almost no interfering effects of other oil molecules are observed.

Overall absorption forces and the water content of solution in the equilibrium state are determined by a Gibb's energy of mixing.

$$\Delta G_{mix} = \Sigma n_i \mu_i$$

and the driving force is chemical potential

$$\mu = \mu^o + RT \ln a.$$

$$\mu - \mu^o = RT \ln a.$$

n_i = Amount of agent i in moles
μ = Potential in solution
μ^o= Potential of pure water
R = Gas constant
T = Temperature
a = Activity

This is connected to the mole fraction so that the activity $a = \gamma * x$, x is a mole portion of the saturation and coefficient γ is a function of pressure, temperature and concentration and it is specific for each system.

$$a_w = ERH = \gamma * (ppm/ppm_{sat})$$

if $\gamma = 1$ then
$a_w = (ppm/ppm_{sat}) = RS$

a_w = Water activity
ERH = Equilibrium relative humidity %
ppm_{sat} = Saturation ppm
RS = Relative moisture saturation %

The absorption forces at the molecular level are binding forces between the water molecules and the molecules in oil.

WATER SOLUBILITY OF OIL

Water solubility of oils is exponentially temperature dependent. The warmer the oil the more water it can hold. This is opposite to the characteristics of solid insulation.
Figure 4 presents the average water solubility of mineral transformer oils i.e. their saturation curve. Solubility is affected also by additives and aromatic compounds of oil.

However, commercial mineral transformer oils typically have a small variation of the amount of additives or aromatic compounds and thus their water solubility is very similar. It's important to note that other dielectric liquids like synthetic esters or natural esters have significantly higher water solubility than mineral oils.

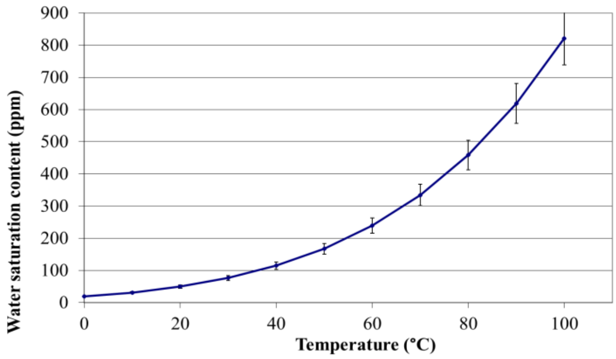

Figure 4. Average water solubility of mineral transformer oil presented as average curve. Data is from several published curves as well as Vaisala own laboratory analysis of commercial oil samples. The variation (-+) between solubility values is shown in the graph.

Aged and contaminated oil has been reported to have typically higher solubility than new or like new oil [9,10,11,12]. Solubility increases as the amount of polar molecules from chemical reactions of oil and cellulose ageing processes increase, in practice the chemical composition of oil changes. However, it is possible that the saturation level of aged oil is lower than new oil as shown in Figure 5, which has also solubility curves of aged mineral oils. Tr1 is an old still operating distribution transformer; Tr2 scrapped, old distribution transformer and Tr3 operating, old industrial transformer. It is assumed that less exponential temperature dependency of Tr2 and Tr3 oils is due to their chemical composition. Unfortunately, it was not yet possible to make a full analysis of those.

Table 1 Solubility coefficients (A, B) for new, unused oil (IEC60422, Vaisala) and three of aged, serviced oils. *[13]

	IEC60422*	Vaisala	Aged oil 1	Aged oil 2
A	7.0895	7.3694	6.835	6.379
B	-1567	-1662.7	-1486.4	-1347.4

If the water content in oil increases so that its amount is equal or bigger than the maximum oil can hold at that temperature saturation occurs. Oil is also saturated with water when temperature decreases below the saturation temperature and the actual water content (ppm) in oil becomes higher than the maximum at this new lower temperature.

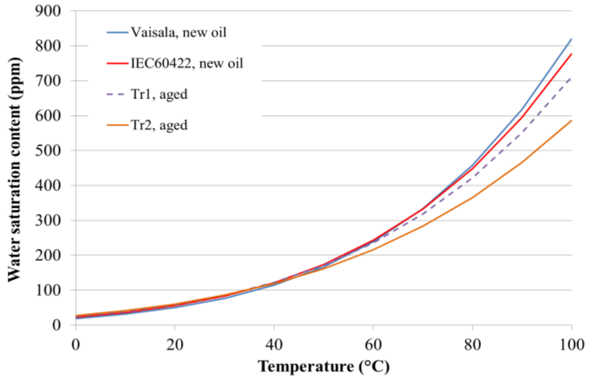

Figure 5 Water solubility curves (saturation) of aged and new oils calculated using the coefficients shown in Table 1.

MOISTURE AND DIELECTRIC STRENGTH OF OIL

Dielectric strength is one of the most important parameters of the transformer oil. It has been reported that the breakdown voltage is affected by several factors, such as moisture, particles, acidity and pressure [9,14,15]. A recent study shows that it is rather the relative moisture saturation (%RS) of oil than the absolute moisture (ppm) that affects the dielectric strength of oil. The results were practically similar for all the tested oils. When the moisture was expressed relative to saturation, the breakdown voltage remained high at the moisture saturation that was below 20 %RS but then decreased significantly with increasing moisture [16].

ON-LINE MOISTURE MONITORING

Online moisture monitoring allows an operator to see the moisture migration trend over a long period term as a transformer-specific pattern.

Moisture in oil may have a significant effect on the loading capacity of a transformer because a high moisture level (%RS) reduces the dielectric strength of oil [16], thus the operational loading limit of a transformer with high moisture may differ from its nominal limit.

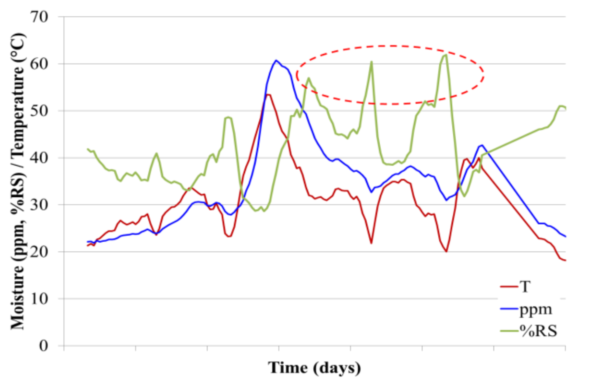

Figure 6 Monitoring data, 7days, from a 10 MVA transformer (ONAN): temperature and oil moisture as %RS and ppm. Sensor located after the cooling radiator.

Knowing the moisture-induced momentary change in the breakdown voltage could be useful regarding the transformer operation. By monitoring relative saturation of oil, an operator can get a warning, if moisture increases to level where there will be a dramatic drop in the dielectric strength of oil, which increases the risk of dielectric faults. This may happen, for example, after heavy loading of a wet transformer, where increasing temperature drives water from solid insulation to oil (Figure 6). When this oil then cools down relative saturation can peak at a high level because absorption of water back to paper may take even days.

The monitoring provides the operator with real-time data to detect early signs of faults and correct them. The transformer-specific moisture dynamics pattern received from online moisture monitoring can be used as input for operational loading guidance.

Effect of sensor location

The moisture sensor should be installed in a location where it is in direct contact with truly representative oil of the transformer. A sensor in the oil cooling circulation line has proven to be the most beneficial for two reasons. First, the oil is certainly representative and secondly, the oil flow improves the sensor response time significantly, so that the measurement values are representative and real-time.

The very bottom of the transformer tank should be avoided if it is not evident that there is true oil exchange present. Without the oil flow at the bottom, the sensor might be measuring just still sludge not the real conditions of the sludge.
Relative moisture saturation (%RS) is strongly temperature dependent, which must be taken into account when choosing the sensor location. If the operator wants to have the most representative figure on the conditions inside the upper part of the transformer tank e.g. relative moisture saturation to define paper moisture of the transformer, the sensor location in the top cooling pipe as close to the tank as possible gives the most realistic results. Again if the operator wants to avoid high relative saturation, then locate the sensor after the cooler/radiator.

One set of moisture and temperature sensors at the top and another set at the bottom can be used to estimate dynamically temperature and moisture gradient during transformer operation under varying loading conditions. This may be especially useful for older ONAN transformers with significantly varying loading conditions.

If the solubility characteristic of oil in use is well known also momentary saturation temperature can be calculated in the system to avoid water saturation and thus a dielectric breakdown. It is also possible to utilize winding temperature if available and model relative moisture saturation deviation close by the windings.

Figure 7. Example of a moisture sensor probe installed in the oil cooling circulation line (top)

Moisture assesment of solid insulation

There are publications [9,10] but not any standardized method to derive paper moisture from the online measured relative moisture saturation of insulation oil.

If the relative saturation is rather stable and long averaging is used, moisture of paper can be roughly estimated from the average temperature and relative moisture saturation. From the data shown in Figure 1 the average top oil temperature and relative moisture saturation values are 32°C and 13.4 %RS respectively. The moisture sorption isotherms for new kraft-paper give an estimated paper moisture of ~3.8% [9,10]. Fessler approximation gives roughly the same paper moisture level. However, the reference temperature used in this example is not exactly the winding temperature, but top oil temperature, thus the derived paper moisture value is just a rough estimate. Also the transformer in question is already over 40 years old, and it is not clear how well the isotherms of the kraft-paper apply to aged solid insulation.

Oil moisture in ppm as a function of temperature gives a better view on the amount of water that is available for the moisture exchange process between the paper surface and oil. This moisture exchange pattern of a transformer can be better utilized as input in conversion algorithms of paper moisture [17].

Also usefulness and effectiveness of online dryers can be evaluated from the amount of water available in oil during varying loading conditions.

Benefits of online monitoring

Benefits of online moisture monitoring with capacitive sensors:

1. Capacitive sensors measure the relative moisture saturation in oil real-time.
2. Measured relative moisture saturation is inherently valid also in other insulation liquids like synthetic or natural esters.
3. Oil ageing and its effect on moisture saturation is negligible, because it is intrinsically included in the initial measurement value.
4. The sensors are easy to integrate into a larger

monitoring system.

5. The monitoring data of moisture and temperature can be used as input for example to transformer ageing models, thermal models, bubbling prediction models and moisture assessment of solid insulation.
6. Errors related to oil sampling, transportation and handling in a laboratory and titration are excluded.

CONCLUSIONS

Besides slow moisture ingress processes, such as cellulose degradation, there may be considerable short-term variation in the moisture of the transformer oil driven by changes in the transformer loading and ambient temperature.

The change in the relative moisture saturation is caused by moisture exchange between the oil and cellulose and the temperature-dependency of water solubility.

As the dielectric strength of insulation oil is affected by higher relative moisture saturation, also the dielectric strength of oil may fluctuate during the transformer operation. Knowing the moisture-induced momentary change in the breakdown voltage could be useful regarding the transformer operation and maintenance.

By monitoring relative moisture saturation of oil, an operator can get a warning if moisture increases to a level where there will be a dramatic drop in the dielectric strength of oil, which increases the risk of dielectric faults. The monitoring provides the operator with real-time data to detect early signs of faults and correct them.

The online moisture monitoring gives the operator the true moisture patterns on the transformers of the utility's fleet. This information can be used both for maintenance as well as operational purposes like applying online drying and as input to loading guidance.

Moisture and temperature data can also be used to estimate moisture content and even distribution in the solid insulation. The authors do not have an opinion whether %RS or moisture in ppm is more suitable for such an assessment, because both parameters have their pros and cons. More studies are needed to get a better understanding. However, moisture values received from a longer period of online monitoring are likely to give a more representative figure on the insulation moisture than just single oil samples taken once a year.

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