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Moisture assessment in power transformers

Lessons Learned

The need to know the water content of paper accurately under all operating conditions is essential for the safe operation of transformers. To improve existing methods of determining the water content of paper, a concept of "water-in-paper activity" has been developed. The water solubility parameter is of paramount importance for the accurate evaluation of water content. A stand-alone software application, the Transformer Moisture Monitor (TMM), is recommended for moisture assessment. The development of a new classification procedure provides a means of ranking dry and wet transformers.

Water in transformers appears as an unwanted substance, decreasing insulation breakdown strength and shortening transformer life dramatically. High water content in paper may result in bubbling, the formation of free water and an increased risk of dielectric breakdown. Water also causes accelerated paper aging, corrosion of core/tank and progressive consumption of oil additives.

Water contamination in transformers comes from three main sources: residual moisture in the "thick structure elements", ingress from the atmosphere, and the aging decomposition of cellulose and oil.

Residual moisture in a new transformer after factory dry out, prior to transportation, is expected to be less than 1%, with a target value of 0.5%. Excessive residual moisture of 2-4% can remain in some thick insulation components, particularly plastics[1]. During service, this moisture gradually seeps into the oil, increasing the water content in the thin insulation structure[1].

Atmospheric water is the main source of transformer contamination. Three mechanisms are acting here: the absorption of water from the direct exposure of the insulation to the air (installation and repair works), the ingress of moisture in the form of molecular (Knudsen) flow due to the difference in the water concentration in the atmosphere and in the oil in the tank, and the viscous flow of wet air into the transformer caused by the difference between the atmospheric pressure and the pressure in the tank[1].

The molecular flow of moisture is practically negligible. The main mechanism of water penetration is the viscous flow of wet air through "poor sealing", i.e. through the sealing points of bushings, the explosion vent and the cooling circulation loop etc., due to the pressure gradient. Large amounts of rainwater can be pumped into the transformer in a very short period of time (just a few hours) if there is improper sealing and a rapid drop in pressure[1].

Methods and instrumentation for moisture measurement

The term "moisture" in the transformer industry is commonly used to indicate water which is absorbed in the paper or dissolved in the oil. Occasionally, the terms "water" or "water content" are used as an alternative way to describe the same substance.

Water in transformers can be found in different parts of the insulation system. It can accumulate in solid insulation, be dissolved in oil, or be found in the form of liquid water at the core or bottom of a transformer. Depending on the media, different methods and instrumentation are used for moisture measurement. For example, to evaluate water content in oil, polymer relative humidity/relative saturation sensors are frequently used. By measuring the relative saturation of oil one can easily determine its absolute moisture content expressed in parts per million (ppm). In this case the water solubility characteristic for the specific oil must be known in advance. Being a real-time efficient on-line method, the moisture-in-oil measurement has attracted a lot of attention in recent years. A number of commercially available sensors have been tested in different conditions using the Monash test rig.

Another method for ppm determination is a technique based on the well-known Karl Fischer titration reaction. However, this method is not a real-time one and requires appropriate chemical instrumentation for its implementation. It is also prone to a high level of error and its results are often difficult to interpret. A timely and accurate measurement of the oil temperature should be made when obtaining the oil sample.

There is also a group of methods based on the measurement and analysis of dielectric properties of insulation. Diagnosis with these methods is based on the fact that paper and oil change their dielectric properties when moisture levels increase. Therefore, by measuring parameters such as the dissipation factor, polarization and depolarization currents (PDC) and return voltages (RVM) in the frequency and time domains, it is possible to relate these changes to water concentration in a paper-oil insulation system. However, with most of these methods it is difficult – if not impossible – to distinguish the effects of moisture on the insulation from the effects of aging caused by other processes. This creates a lot of confusion over the reliability of dielectric response methods. Interpretation of the results still remains more art than science.

Water content of paper insulation

One of the aims of the moisture assessment of oil-filled power transformers was to evaluate the water content of its paper insulation. The term "paper insulation" is a generic term that describes solid cellulose material, such as paper, pressboard, wood and cotton. Another term, "water content of paper (WCP)", is used to quantify the amount of water present in paper insulation. Traditionally, the term WCP refers to a ratio between the mass of water and mass of dry non-oily paper, expressed in a percentage. The mass of water is calculated from the difference between the masses of wet and dry paper. The paper is usually dried out in an oven prior to the measurement of the dry paper mass. The traditional term WCP gives a clear meaning for non-oil-impregnated paper.

For oil-impregnated paper the WCP can still be measured, in this case using the Karl Fischer titration method. Following the measurement of water mass in the Karl Fischer apparatus, the oily paper is degreased and only then placed in an oven for drying. To obtain an accurate measurement, the thickness of the piece of paper or strip of pressboard should not exceed a few hundred microns. However, for a paper-oil insulation system with both thin and thick paper insulation the situation for measuring the WCP is completely different.

In a study conducted at Monash University under an EPRI, USA sponsored project, a new method of moisture assessment in operating transformers was developed, based on a water-in-paper activity concept. The parameter of water-in-paper activity is used to access moisture conditions in both new and old transformer insulation systems. Another term, "active water content of paper (WCP_A)", was also introduced. The term WCP_A reflects the water available in the transformer insulation for exchange between paper and oil. A new moisture equilibrium chart (shown in Figure 1) relating the parameter of water-in-paper ➤

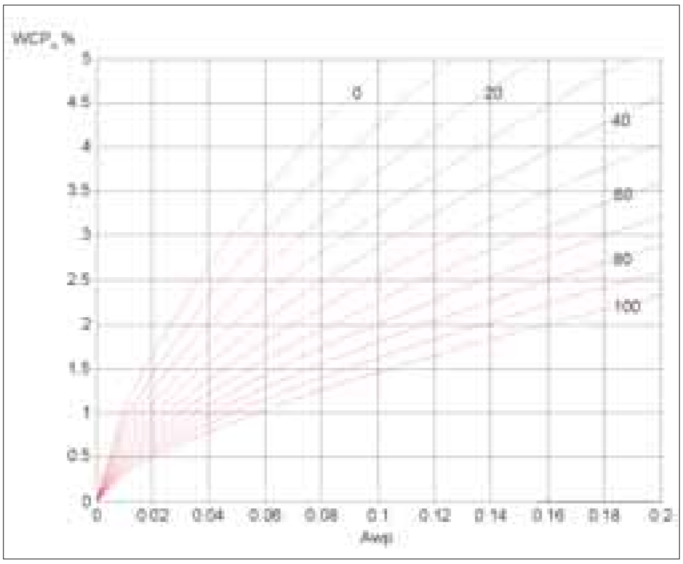

Figure 1. Moisture Equilibrium Curves relating water-in-paper activity to active water content of paper for temperatures from 0 to 100 °C.

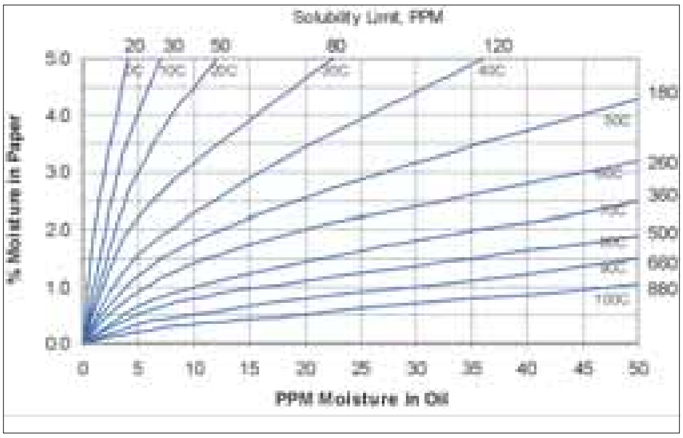

Figure 2. Moisture Equilibrium Chart as published in "Moisture Equilibrium Charts for Transformer Insulating Drying Practice".[2]

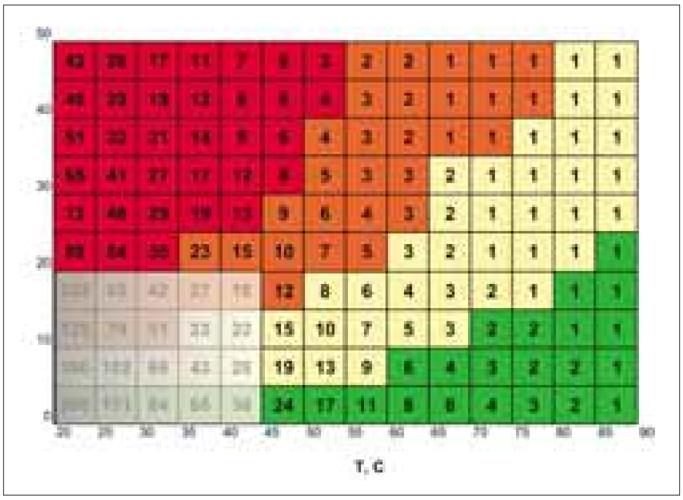

Figure 3. Chart for off-line moisture diagnostics of transformers containing new oil.

activity to the WCP_A was developed.

Numerically, water-in-paper activity (A_{wp}) is equal to the equilibrium percentage of relative saturation (RS_{eq}) divided by 100.

There are a number of ways to evaluate the WCP_A of paper insulation in a paper-oil insulation system. One of them is apparent from Figure 1. To use the curves of Figure 1 we need to establish equilibrium conditions in the system and measure the parameter of A_{wp} using a relative saturation (RS) sensor.

Another way to evaluate the WCP_A of paper insulation in a paper-oil insulation system is to use a moisture equilibrium chart, similar to the well-known moisture equilibrium chart published in 2 and shown in Figure 2.

The chart in Figure 2 gives the relationship between the water content of oil (WCO) expressed in ppm, the temperature and the "% Moisture in Paper", which, in fact, for thin paper insulation is equal to the WCP_A. Again, to evaluate the WCP_A, we need to establish equilibrium conditions in the system and then measure the WCO using the Karl Fischer apparatus. However, we must measure one more parameter in this case, prior to the evaluation of the WCP_A. This parameter is called the "water solubility of oil S(T)", or, as in Figure 2, the "Solubility Limit, ppm".

The moisture equilibrium chart in Figure 2 was developed for new oil. The figures around the chart show the water solubility parameter S(T) for new oil at temperatures from 0 to 100 °C in 10 °C intervals.

Assessment of moisture in an operating transformer

It is known that an operating power transformer is never in moisture equilibrium. Thus, the two moisture equilibrium charts in Figures 1 and 2 cannot be applied directly when assessing moisture in the field. To address this, a method for the moisture assessment of transformer insulation has been developed. The method is based on the Monash water-in-paper (WIP) algorithm, which incorporates the following three steps:

- Evaluation of true oil relative saturation in the transformer
- Evaluation of the water-in-paper activity (A_{wp}) for the transformer oil
- Evaluation of the active water content of paper (WCP_A) as a function of A_{wp} and temperature.

A software application, the Transformer Moisture Monitor (TMM), has been developed on the basis of the WIP algorithm. The TMM uses neuro-fuzzy computing to evaluate the consistency of the moisture sensor output, to access the WCP_A, and to alert the user when insulation conditions require attention. The TMM acquires data from the Vaisala HMP228 Humidity and Temperature Transmitter. The probe of the transmitter has both moisture and temperature sensing elements at its tip.

New classification procedure for off-line moisture diagnostics

The research conducted at Monash University has shown that, for the accurate moisture assessment of transformer insulation, the continuous monitoring of a number of parameters, including transformer load, temperature and oil relative saturation, is required. The measurement of water solubility characteristic of oil in the transformer is also required.

A utility may operate tens or even hundreds of transformers. However, not all of the transformers require continuous monitoring. How is it possible to identify a transformer with moisture concerns for further monitoring? There is a demand for a classification procedure, which would rank transformers by moisture levels.

A traffic light approach is the EPRI adopted way of ranking the health of plant equipment. Red, yellow and green colors would indicate the 'wet', 'requires attention' and 'dry' states of moisture in transformers.

A new classification procedure was developed to rank, from a population of power transformers, critical transformers in terms of moisture for further continuous monitoring. The new classification procedure aims to improve the effectiveness of the management of transformer life.

The new classification procedure is based on a method of moisture assessment that evaluates the WCP_A and was briefly described in the section above. It is available in the form of a chart, shown in Figure 3. Values of WCO in ppm represent the results of Karl Fischer (KF) measurements and values of the temperature T represent the temperature of the oil at the moment of oil sampling. In Figure 3, values of WCP_A are distinguished by color. Green corresponds to a WCP_A of less than 1%, yellow corresponds to a WCP_A of between 1% and 2% and red corresponds to a WCP_A of more than 2%. The numbers in the squares represent the diffusion time constant for moisture across a 1-mm pressboard plate exposed to oil from both sides. The 1-mm pressboard was chosen to reflect the approach of the water-in-paper activity applied to the transformer ranking and classification.

At an oil temperature below 45 °C and WCO of less than 20 ppm, the moisture diffusion time is too long for the reliable diagnosis according to the proposed procedure. To reflect this fact the bottom left corner of the graph in Figure 3 is shadowed.

The classification procedure chart in Figure 3 is valid for oil with a water solubility characteristic close to that of new oil. In the previous section of this paper it was demonstrated that the water solubility characteristic of new and aged oil can differ significantly. This means that for the accurate ranking of aged transformers, evaluation of the oil's water solubility characteristic would be required.

In light of the new knowledge presented here, the traditional approach, which states: "If the WCO exceeds 20 ppm, the transformer requires further attention, if the WCO is less than 20 ppm no action is required," must be reconsidered. From Figure 3 it follows that at WCO=20-25 ppm a transformer with new oil would be considered "probably wet" if the oil sample was taken at a temperature of below 55 °C. However, if the oil sample was taken at a temperature of above 80 °C, with the same WCO=20-25 ppm, the transformer would be considered "probably dry". To prove or reject the conclusion, one more sample of oil should be taken in the number of hours shown in the related square on the chart. This example illustrates the importance of the measurement of oil temperature during the oil sampling, the importance of the second oil sampling, and the importance of the length of time between the two sampling events.

It is apparent that knowledge of the WCO only, gained from a single Karl Fischer measurement, is insufficient for the accurate assessment of transformer moisture condition. Knowledge of the temperature of the first oil sample, the dynamics of moisture and temperature gained from the second oil sample, and the water solubility of the oil are also required.

Conclusions

Oil type, age and flow rate contribute to the measurement and subsequent accuracy of moisture assessment in a paper-oil insulation system. Sensor positioning also contributes to the accuracy of moisture assessment.

The parameter of the water solubility of oil is required for the validation of the moisture sensor installed in the transformer. Water-in-paper activity was found to be a factor in determining the state of dryness in a power transformer.

A stand-alone software application called "Transformer Moisture Monitor" (TMM) is proposed for the moisture assessment of a transformer.

A new classification procedure that aims to identify critical units for further continuous monitoring is suggested for the ranking of power transformers by the level of moisture. Red, yellow and green colors would indicate the 'wet', 'requires attention' and 'dry' states of moisture in transformers. The classification procedure presented is only valid for oil with a water solubility characteristic close to that of new oil. For the accurate ranking of an old transformer, the water solubility characteristic of the transformer's oil would need to be evaluated. ●

References:

1. *V. Sokolov and B. Vanin, "Experience with In-Field Assessment of the Water Contamination of Large Power Transformers", Proceedings of EPRI Substation Equipment Diagnostics Conference VII, New Orleans, 1999*
2. *T. V. Oommen, "Moisture Equilibrium Charts for Transformer Insulating Drying Practice", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-103, 10, 1984, pp.3063-3067*

The determination of moisture in oil is an essential part of a comprehensive transformer maintenance program.

HMP228 Moisture and Temperature Transmitter for Transformer Oil

The HMP228 Transmitter provides on-line measurement of moisture and temperature in transformer oil. The measurement gives continuous information and enables better maintenance against transformer failures.

Vaisala's microprocessor-based HMP228 Transmitter is accurate, reliable and fast. The basic model of the HMP228 Transmitter calculates the average water solubility in mineral transformer oil. The water solubility in oil is temperature dependent: water solubility increases as temperature raises. In addition to traditional ppm-output, the transmitter measures water activity (a_w) indicates directly whether the oil is too moist. The a_w measurement is independent of the type, aging or temperature of the oil. ●