# Assessing Water Content in Insulating Paper of Power Transformers

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***Abstract* — Moisture content of solid insulation is a persistent concern for a power transformer as it causes several detrimental effects on the insulation's integrity. Moisture content assessment is often derived from a single oil sample submitted to a Karl Fischer test in laboratory although it is recognized that a single oil sampling cannot reveal the moisture content in paper if the oil temperature is unstable. On-line monitoring systems are available and continuous recording allows integration of temperature variations and the computation of a dependable value for moisture content in paper. Collection of data over a long period allows calculation of moisture content of the various components of the solid insulation system even if they are at different temperatures and characterized by different diffusion rates. Field data is presented for an application on a large power transformer along with the model used to derive the water content of insulating paper from water content in oildespite continuously varying temperatures.**

***Index Terms* — liquid-immersed power transformers, monitoring, insulation system, partition curves.**

## I. Introduction

Moisture management in power transformers is a persistent concern especially for aging units. Extensive drying procedures are applied at the manufacturing stage and sustained efforts are deployed in service to maintain high dryness. The effect of moisture on insulation aging is well documented along with the detrimental effect on insulation strength and partial discharge inception level.

It has also been demonstrated that at high temperatures, the residual moisture in winding insulation can trigger the release of free gas bubbles, thus creating an immediate threat to the dielectric integrity of the insulation structure. Assessment of water content in solid insulation is rightfully an essential part of any comprehensive condition assessment program. In the former version of IEEE® Std 62 – 1995 (1) the moisture content in solid insulation was defined as follows:

Dry Insulation 0 – 2%
Wet Insulation 2 – 4%
Very Wet Insulation 4.5%+

In the more recent IEEE Std C57.106 – 2002 (2) the permissible moisture level in paper is inferred from values of water content in oil, assuming thermal stability and moisture equilibrium between paper and oil:

| Transformer rated voltage | Maximum water content in oil ppm | | | Equivalent water content in paper |
|---|---|---|---|---|
| | 50°C | 60°C | 70°C | |
| Up to 69kV | 27 | 35 | 55 | 3% |
| 69 to 230kV | 12 | 20 | 30 | 2% |
| 230kV and above | 10 | 12 | 15 | 1.25% |

The traditional method of moisture monitoring calls for oil sampling at regular intervals. The oil sample is then processed through a Karl Fischer titration method that provides the total water content in oil in parts per million (ppm). Most of the water is in the form of dissolved water and is available to move from the oil to the solid insulation as the transformer progresses toward equilibrium. However, some of the measured water is chemically bound to chemical agents such as by-products of oxidation. This bound water is only partially available to migrate from the oil to the paper. As the oil ages, the quantity of chemical agents due to oxidation increases and these agents provide additional sites for the water to bind to. Some of the water may also bind to particles in suspension in oil, and this water would not be fully available to move to the solid insulation. In spite of these constraints, this method remains the most commonly used to assess the moisture content of solid insulation. Equilibrium curves have been developed to relate absolute water content in oil to water content in paper (Figure 1).

Application of these curves implies that the transformer is under a thermal equilibrium.

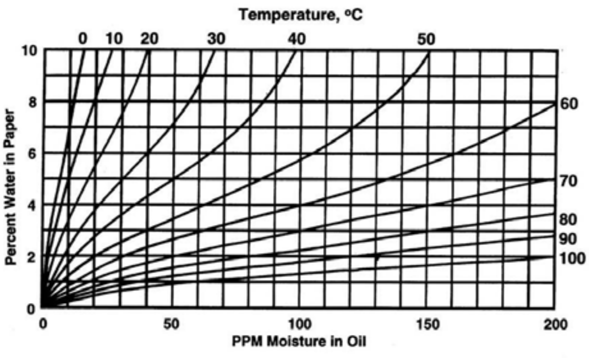



Figure 1 - Equilibrium Curves for Moisture Partition Between Oil and Paper (ppm vs. WCP)(3)

Measuring directly the relative moisture saturation (RH %) makes it unnecessary to consider the type or condition of the oil. The relative saturation is the percentage of full saturation and is the most representative figure of the water available in oil for transfer to the paper. At equilibrium the relative saturations of both components of the insulation system (the oil and the paper) are equal. Commercial on-line moisture monitoring sensors usually provide a relative saturation measurement as well as the measurement of the oil temperature at the location of the moisture sensor. From these two measurements (and with knowledge of the oil saturation curve for this type and this age of oil is available), the relative saturation can be converted in absolute water content in oil in ppm (WCO). At equilibrium, the relative saturation of oil is the same as the relative saturation of paper in contact with the oil. In this condition, the equilibrium curve relating water in oil to water in paper (Figure 2) can be applied to determine the water content of paper (WCP).

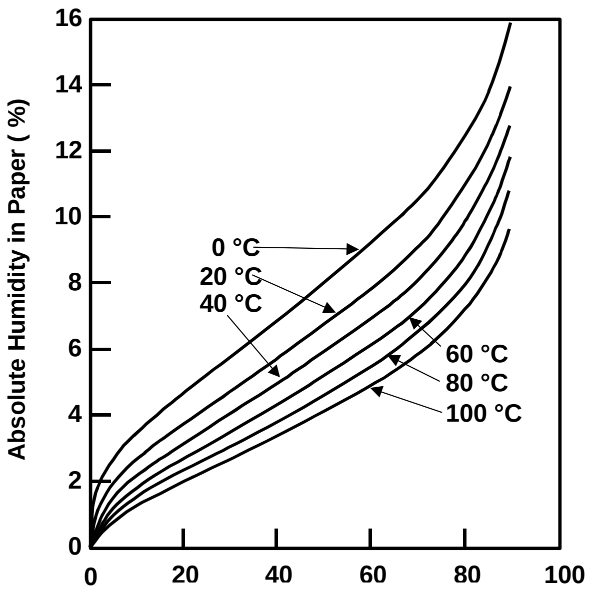



Figure 2 - Equilibrium Curve for Moisture Partition Between Oil and Paper (RH % vs. WCP)(4)

## II. WATER DISTRIBUTION UNDER STEADY THERMAL CONDITIONS

It is important to recognize that in normal operation, even though a stable thermal condition can be created, there still are temperature differences, and therefore different moisture contents, in the various parts of the insulation structure.

For example, we may consider a naturally cooled transformer with a temperature drop of 20 °C between top oil and bottom oil at full load. Assuming an ambient temperature of 20 °C and thermal equilibrium, the temperatures shown in Figure 3 for oil and winding are typical. If a moisture sensor, installed at the bottom oil temperature, shows a relative saturation of 22 %, we can deduce, from the equilibrium curves in Figure 2, the moisture content indicated in Figure 3, for the different parts of insulation. These different moisture levels need to be considered in the condition assessment of transformer insulation.

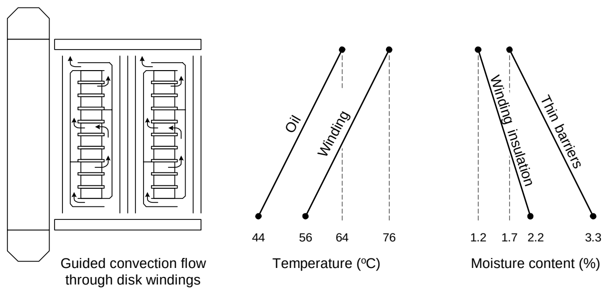



Figure 3 - Moisture Content on Critical Insulation

In order to understand the diffusion process, it is of interest to consider the total amount of water in each component of the transformer. Table 1 shows the weight of each component estimated for the transformer described in Section 5. The thick insulation and the thin barrier can be assumed to be at the same temperature, in line with the average oil (54 °C) while the winding insulation is at the average winding temperature (66 °C). With these assumptions, the water distribution among the various components has been calculated and the results are shown in Table 1. It can be seen that in this thermally stable condition, about half of the water is in the thick insulation; as for the oil, the solid insulation can be regarded as an infinite reserve of water.

Table 1 - Moisture Distribution Under Steady Thermal Conditions

| | Oil | Thick Insulation | Thin Barrier | Winding Insulation | Total Water Content |
|---|---|---|---|---|---|
| Total Mass | 45,000 kg | 2,250 kg | 900 kg | 1,350 kg | |
| Full Load Conditions | 26 ppm<br>1.2 kg | 2.4 %<br>54.0 kg | 2.4 %<br>21.6 kg | 1.6 %<br>22.0 kg | 98.8 kg |
| Off Service Conditions | 1.3 ppm<br>0.1 kg | 2.2 %<br>49.4 kg | 2.2 %<br>19.8 kg | 2.2 %<br>29.5 kg | 98.8 kg |

## III. Water Distribution Under Transient Thermal Conditions

In practice the thermal stability conditions are never achieved. Beside load variations, the transformer is submitted to daily and seasonal temperature variations. With temperature conditions continuously varying, the equilibrium curves cannot be applied directly; therefore it is not possible to assess correctly the water content of insulating paper from a single sampling of insulating oil and a Karl Fischer test in laboratory, even if the oil temperature is noted at time of sampling.

Temperature changes entail displacement of water from paper to oil or vice versa. The diffusion rate for this process depends on the temperature, but also on the thickness of solid insulation, on the area of contact between circulating oil and paper, and on the moisture content of paper. The diffusion time constants reported in literature for thin insulation (1 mm) are summarized in Table 2(6). Diffusion time constants are also indicated for thicker materials, assuming the time constant increases with the square of the material thickness. It is recognized that in a transformer the construction is complex and the equivalent thickness of insulating material has to be estimated for each specific structure.

Table 2 - Diffusion Time Constant for Oil-Impregnated Pressboard Insulation (in Days)

| Temperature | Insulation Thickness | | |
|---|---|---|---|
| | 1 mm | 2 mm | 4 mm |
| 80 °C | 0.9 | 3.6 | 14 |
| 60 °C | 4.2 | 17 | 67 |
| 40 °C | 20 | 79 | 317 |
| 20 °C | 93 | 373 | 1493 |

These slow diffusion rates make it necessary to average the recorded data over a long period. Moreover, the averaging period has to be adjusted according to the oil temperature and the thickness of the insulation to be assessed. This is best done with on-line monitoring providing data acquisition of moisture in oil and relevant temperatures.

## IV. On-Line Monitoring of Moisture Content in Transformer Insulation

Several on-line monitoring systems are available to record the variations of moisture content in insulating oil. However, the concern over moisture content in paper might not warrant by itself the deployment of expensive monitoring systems over a large population of transformers. An interesting solution is to combine the real-time moisture in oil measurement with a more essential monitoring function such as the real-time detection of fault gases dissolved in oil.

This is the avenue selected for the HYDRAN* M2 that combines two functions. The first one is the detection of incipient fault in the transformer insulation. On-line monitoring of hydrogen and CO has long been recognized as an excellent method for the detection of dielectric and thermal problems. Detection at an early stage is the best means of reducing the risk of failures and forced outages. This functionality has been provided by the Hydran technology for many years. For a minimal additional cost, a moisture sensor is now available with the HYDRAN M2. The moisture detector is a thin-film capacitive sensor that is sensitive to relative saturation. The use of capacitive sensor for the measurement of oil relative saturation was pioneered by TV Oommen(5) and these sensors are now available from many sources. The RH % reading can then be converted to absolute moisture content in ppm. As an option, configurable analog inputs are provided to allow for recording of significant parameters such as top oil temperature, bottom oil temperature, and load, which are required for an assessment of the solid insulation moisture level.

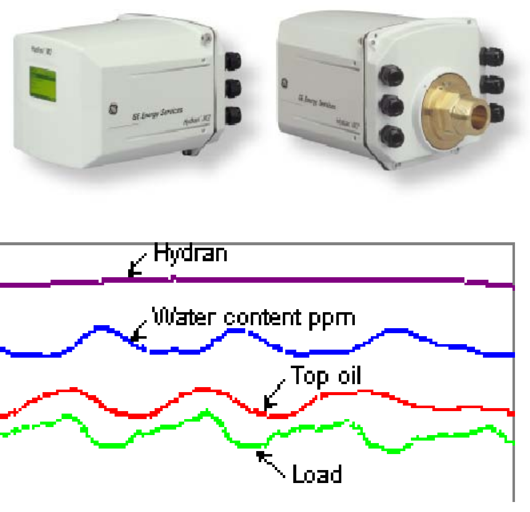



Figure 4 - HYDRAN M2 Sensor With Display of Typical Recorded Data

With such a device, it is possible to record data over a long period. This data can be processed with a suitable algorithm that takes into account the variations of winding and oil temperature on the dynamic process of water migration.

Relative saturation needs to be recorded along with the oil temperature at the sensor. Top oil and bottom oil can also be recorded along with load to determine the temperature in the insulation components that are of most interest. This data is averaged over time to account for the slow diffusion rate involved in the migration of water between paper and oil.

## V. FIELD DATA

In August 2003, a 50 MVA, 230 kV transformer was equipped with HYDRAN M2 sensor and a continuous string of data was made available from the data logging function for off-line processing. It is an old unit, core type, 55 °C rise with a nitrogen blanket. The sensor is mounted on a spare cooler outlet at the bottom of the tank between the two sets of coolers.

Figure 5 shows one week of data where the daily variation of moisture content in oil is clearly visible along with the relative saturation and the top oil temperature. Since the thermal conditions are continuously changing, it is impossible from a single measurement to assess the water content in insulating paper. Depending on the sampling time, the computed value of water content in paper at top oil temperature could give any value from 1.3 % to 2.5 %, which is almost a two-to-one variation. However, if this data is recorded over a long period, it is possible to determine the moisture content of the various components of the insulating system taking into account physical characteristics of solid insulation, diffusion rate and temperature.

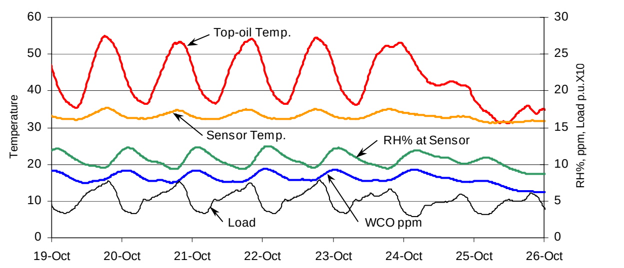
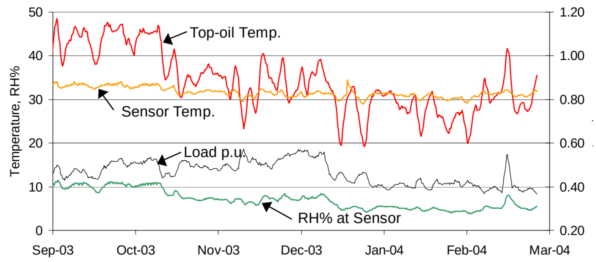



Figure 5 - Data Logging for One Week in October 2003

Figure 6 shows the main data recorded over a period of six months from September 2003 to March 2004. It can be seen that the loading is fairly stable between 0.5 p.u. in the fall, reducing to 0.4 p.u. in winter. The transformer is running quite cold with top oil temperature ranging from about 45°C in the fall to 25°C in winter. Using the top oil temperature, load and transformer characteristics, it is possible to calculate the bottom oil temperature and hot-spot temperature. Daily variations have been filtered out from these data to better show the long-term trend.

Figure 6 - Data Logging Over a Period of Three




Months

The insulation structure is made of several components that need to be evaluated separately in term of moisture content. The first component of interest is the winding insulation paper because the moisture content has a direct influence on insulation aging and on the probability of releasing bubbles should an overload occur. This component is fairly thin and experimental evidence has shown that in regard to diffusion rate, disk winding can be assimilated to a 1-mm paper(6). As can be seen in Figure 7, the average hot-spot temperature, over the first month of data logging, is about 50 C leading to a diffusion time constant of about 9 days. But, as the hot-spot temperature drops, the diffusion time constant rises exponentially to reach above 60 days in some cold winter periods. This is taken into account in the calculation and averaging of the water content in paper.

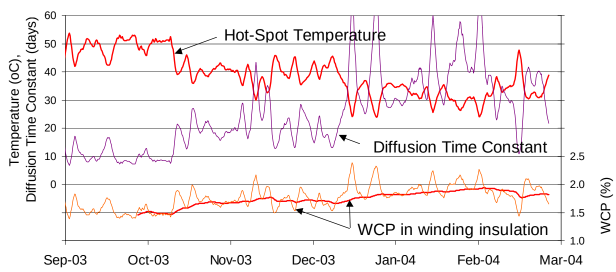



Figure 7 - Derivation Of The Diffusion Time Constant And Water Content In Winding Insulation

A second component of interest is the thin barriers providing main insulation between windings and between winding and tank. In the main insulation, the highest electric field is often found on the barrier closest to the winding. The moisture content in this area is therefore critical for dielectric strength of the main insulation. It is known that an increase in moisture content from 0.5 % to 3.0 % may reduce by 50 % the inception voltage for partial discharges (7). The bottom part of the barriers is more at risk because the cooler temperatures will lead to higher moisture contents. The barriers' temperature is the same as the bottom oil temperature.

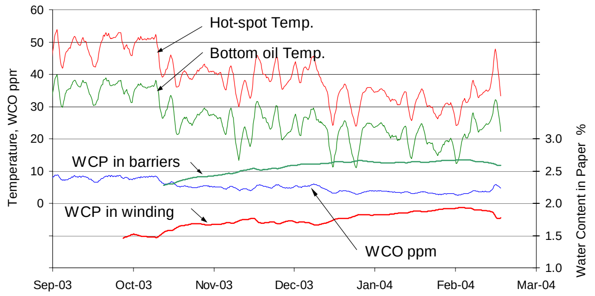



Figure 8 - Long-Term Computation of Moisture Content in Winding Paper and Thin Barriers

Figure 8 shows the temperatures of interest and the moisture contents calculated for winding insulation and barriers. It can be seen that the moisture content of the barrier can be significantly higher than the moisture content of winding paper. This difference will increase with load as it is mainly sensitive to the temperature difference between winding hot-spot and bottom oil.

In regard to thick insulation, data would need to be averaged over a much longer period. The diffusion rate of these components is difficult to assess since thickness varies over a broad range, the surface in contact with oil is also very variable, as is the actual oil flow on these exchange surfaces. It is recognized that a large segment of the water in the transformer is stored in the thick insulation. The moisture content of these components does not lend itself to an easy assessment. Fortunately, thermal aging for these components is usually not a concern and the electric field sustained by the thick insulation is usually much less than the stresses of the thin barriers.

## VI. What to do with Results?

The objective to determine the water content in the solid insulation has been presented, together with the negative consequences of high moisture levels inside the transformer tank. The question raised most often is: now that we know the situation, what do we do?

The obvious answer is to remove the moisture from not just the oil, but where most of the water is hiding, in the solid insulation. The objective is to achieve a level that will not have the negative influences such as excessive aging of the solid insulation and the oil. This is a task for which several techniques have been developed and used in the past with various degrees of success (8).

### *a) Traditional Hot Oil Circulation*

The traditional technique of circulating hot oil through the transformer has been widely used in many countries around the world. This technique has some limitations, starting with the transfomers' removal from service, to the point that once performed, with many passes, the moisture level in the oil rises after a few days or weeks once back in service.

The limiting factor in this process only removes the moisture from the oil and very little from the solid insulation. Once the transformer is returned to service, the heat generated in the windings due to the load, 'push' the moisture from the paper into the 'dry oil'.

### *b) Low Frequency Heating (LFH)*

This technique requires the transformer to be removed from service, with portable equipment brought to the site.

The transformer is disconnected from the grid, and a variable frequency high current power supply is connected to the transformer, together with the traditional oil treatment and vacuum pumps.

The transformer is energized at a frequency of less than 1Hz, and high current in order to heat the windings of the transformer to at least $80^0$C to $90^0$C. Energized from the primary side, with the secondary side is shorted out (as if a heat run were being performed).

Depending on the size of the transformer, two passes or more may be required. This technique is quite effective as it uses heat and vacuum to remove the moisture from the solid insulation.

### *c) Stationary Molecular Sieve Technology*

Permanently installed molecular sieves have proven to be very effective in drying transformers with oil capacities of up to 30,000 litres. The benefits of this technique are that the transformer is not removed from service, but depends on the transformer in service to generate the heat required to move the moisture from the paper into the oil. From there the oil is circulated through the molecular sieve at a slow rate (typically 100 litres per hour) from which the moisture is removed with the use of water absorbent beads.

This technique is obviously a long term one, and to monitor its effectiveness, a monitor such as the HYDRAN M2 with the ability to calculate moisture content in the solid insulation, as described in this paper, provides a most effective method to know when to stop the drying process.

## VII. Conclusion

The effect of moisture on thermal aging and the reduction of dielectric strength are concerns for numerous aging transformers. The moisture content of insulating oil can be readily assessed from a Karl Fischer titration in laboratory. However, if the transformer is submitted to daily temperature variations, a single sampling can lead to large errors on the assessment of water content in paper. On-line monitoring over periods of several months allows for a more dependable assessment.

Moisture content in winding insulation should be treated separately from moisture content in the main insulation. Depending on the type of cooling, the temperature at the winding hot spot can be very different from the temperature at the bottom of the main insulation, thus leading to very different water contents. Because of temperature and insulation thickness, the moisture diffusion rates can also be quite different for these two components.

Combining moisture sensor with more monitoring functionality, such as dissolved gas, makes it more cost effective and allows for dependable determination of moisture content in transformer solid insulation.

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