

# Experimental Evaluation of Water Content In Transformer Oil

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**Abstract:** This paper presents experimental research on temperature dependency of water content in mineral transformer oils. Moisture sensor measurements (online measurement) and absolute water content determination by Karl Fisher titration method (off-line method) were performed in the laboratory to investigate solubility of different types of mineral transformer oils. Results of experiments explain that preset moisture solubility model of moisture sensor affects the accuracy of water content determination. Test setup and procedure for verification and calibration of moisture sensor with specific-oil solubility parameters is described then tested and evaluated. This allows greater accuracy of online water content monitoring in the operating transformers under the changing temperature conditions.

**Keywords:** power transformer oil; water solubility model; relative water saturation; on-line monitoring of water content; temperature dependency of water in oil

## I. INTRODUCTION

Transformer utilities always try to keep the water in the transformer oil at a low level. Water content is a very important parameter for the safe operation, reliability and service life of a transformer. Different maintenance guides are set and used by the utilities for the maintenance of transformers. According to these maintenance guides an accurate measurement of the water level in a transformer becomes a very important factor in transformer maintenance. Transformer oil used in the transformers is usually a highly refined mineral oil. These mineral oils are stable at high temperature levels and have excellent electrical insulating properties. To maintain the oil quality, periodic oil tests are performed and compared with the international standards [1, 2]. In the standards, maximum water content limits are specified as mg of water per kg of transformer oil, (i.e. ppm value), for the new and aged transformers depending on their voltage levels & conditions. For decades, these limits have been widely accepted, assuring reliability of transformer operation. Water affects dielectric properties of both liquid and paper insulation systems of the transformer and thus to aging. Moisture in insulating oil may under fast decreasing temperature, results in free water that can lead to electrical breakdown of insulating oil. Water content increases electrical conductivity and dissipation factor which reduces the electric strength of insulating oil. Thus mass transfer process of water occurs due to the equilibrium imbalance, in which at higher temperatures water leaves the paper to enter the liquid. Water in the insulating oil originates from air moisture in the case of open-breather, and the thermal decomposition of cellulose based solid insulating materials. Water has a strong influence on the life expectancy and loading capacity of the transformer. Water has a strong influence on the electric strength. In a wide range of relative humidity, the electric strength of clean new insulating mineral oil, for the temperatures higher than 0°C, falls practically exponentially as relative humidity [3, 4].

A commercially moisture sensors are available and they can be used as on-line monitoring systems to measure inaccurately the oil temperature and the oil relative saturation. On the other hand, there are some equilibrium curves are available that can be used to calculate the water content in paper from the water content in oil at the equilibrium conditions and these calculated values of water content in paper can be used as the boundary values which can help to evaluate the condition of water content in insulation solid of transformer. Karl-Fischer titration is used to calculate the water level in the transformer oil in the laboratory.

Section II. Describes the water content in oil & Paper insulation system. Section III. Describes the fundamentals of online & offline moisture content monitoring. Section IV. Describes the experiments done. Section V. describes the Results & finally Section VI. Comes to conclusion of the paper.

## II. WATER CONTENT IN OIL AND PAPER INSULATION SYSTEM

Mineral insulating oil has low affinity for water i.e. one drop of water at room temperature is good enough to saturate one litre of new insulating oil. Water molecule is attracted towards the polar oil components such as aromatic hydrocarbons, which are constituents of transformer oil and polar impurities. Lower weight molecular acids, produced during thermal ageing of paper insulation [5], also increase the moisture solubility of water in oil. Water in transformer exists in four typical forms:

- Dissolved water is hydrogen bonded to the hydrocarbon molecules of which oil is composed.
- Emulsified water is supersaturated in solution but has not yet totally separated from the oil. It usually gives oil a milky appearance.
- Free water is also supersaturated in solution but in a high enough concentration to form water droplets and separate from the oil.
- Water adsorbed in cellulose insulation.

In most cases, when one is analysing or discussing the amount of water in oil, dissolved water is being referred to as emulsified, and free water is visually apparent.

### A. Water Solubility

The concepts of solubility can sometimes be difficult to understand, but it is a very important concept when trying to access the dryness or wetness of a transformer. The water solubility is defined as the total amount of water that can be dissolved in the insulating oil at a specific temperature. The solubility of water is not constant in insulating oil but it changes due to temperature variations. If the temperature increases, the amount of water that can be dissolved in insulating oil also increases. This increase is not linear but exponential in function. For example, at 10°C only 33 ppm of water can be dissolved in the insulating oil, whereas when the temperature increases to 90°C then the amount of water that can be dissolved in the insulating oil increases to almost 663 ppm. The calculated solubility limits for oil at various temperatures are shown in Table I. The solubility for mineral oil can be calculated using Arrhenius Equation 1:

$$\text{Log } S = -A/T + B \quad \text{equation (1)}$$

Where: "S" is the solubility of water in mineral oil & "T" is the temperature in Kelvin ( $^{\circ}\text{C} + 273$ )

"A" & "B" are constants. Here  $A = 1670$  &  $B = 7.42$

Different authors chosen different values of constant A & B that is shown in Table II.

TABLE I  
WATER IN OIL SOLUBILITY AS FUNCTION OF TEMPERATURE

| Oil Temperature | Water Content in Oil, ppm |
|-----------------|---------------------------|
| 0°C             | 20                        |
| 10°C            | 33                        |
| 20°C            | 53                        |
| 30°C            | 82                        |
| 40°C            | 122                       |
| 50°C            | 179                       |
| 60°C            | 255                       |
| 70°C            | 358                       |
| 80°C            | 491                       |
| 90°C            | 663                       |
| 100°C           | 880                       |

TABLE II  
 COPARISION OF LITERATURE AND ESTIMATED OIL SOLUBILITY PARAMETERS

| Authors | Oomen | Griffin | Cigre |
|---------|-------|---------|-------|
| A       | 1670  | 1567    | 1640  |
| B       | 7.42  | 7.09    | 7.23  |

### B. Relative Saturation

Relative Saturation (RS) is the actual amount of water content measured in the insulating oil in relation to the solubility of water in oil level at that temperature. Relative saturation is expressed in units of percent & it is the concentration of water (W) in the insulating oil relative to the solubility (S) or concentration of water that the insulating oil can hold at the measurement temperature, as shown in Equation 2.

$$RS = W / S (100\%) \quad \text{Equation (2)}$$

Where: - “W” is in ppm wt. /wt. & “S” is in ppm wt. /wt.

For example, a sample of oil is taken for the determination of the water content in it. The temperature of the oil at the time of sampling is 60°C. The laboratory performed the test and determined the water content to be 11 ppm. From Equation 1, it is calculated that the solubility level at 60°C is 255 ppm. Then the relative saturation is the actual measured value compared to the solubility value at that temperature. In this case it is 11 ppm divided by 255 ppm resulting in a relative saturation of 4.31percent.

### C. Water Concentration In Paper Insulation System

The equilibrium between water content in paper and oil insulation has been widely studied by several authors [6, 7], who obtained the equilibrium curves showing relationship between water content in paper & water content in oil for different temperatures. So it is possible to determine the value of one of these variables once knowing the other one. Reaching equilibrium condition is a long time process. This time varies from few hours to several days depending upon the temperature variation. The time to equilibrium also depends on the direction of water flow. The require time to reach an oil-paper insulation to be in equilibrium condition can be approximately estimated by the equation 3.

$$t = \frac{4d^2}{\pi^2 D} \quad \text{Equation (3)}$$

Where “d” represents the thickness of pressboard insulation & “D” is the moisture diffusion coefficient & “t” is the diffusion time constant for moisture diffusing from one side of solid insulation.

Figure 1 shows Oomen paper-oil moisture equilibrium curves. At different temperatures, paper-oil moisture equilibrium curves vary greatly. Moisture content in transformer oil changes with temperature at operating condition.

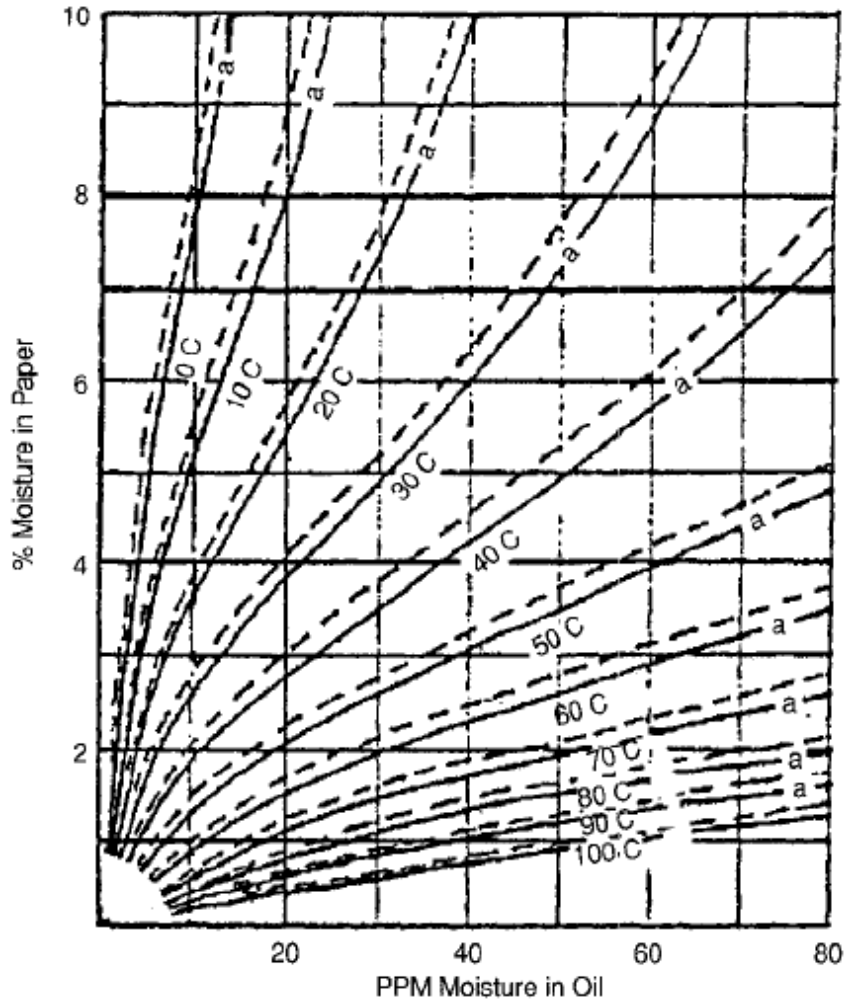


Fig.1 Oomen paper-oil moisture equilibrium curves

### III. FUNDAMENTAL OF ON-LINE AND OFF-LINE MONITORING OF MOISTURE CONTENT IN TRANSFORMER OIL

On-line & off-line monitoring of Water content in transformer oil is discussed here.

#### A. On-Line Monitoring

Doble moisture in oil sensor (as shown in the figure 2.) is used for on-line monitoring of moisture content in transformer oil. The domino measures water in oil in terms of relative saturation (%RS) which can be determined as follows: relative saturation indicates the amount of moisture in oil in the scale of 0-100%RS. In this scale, 0%RS is an indication of completely water free oil & 100%RS is an indication of oil fully saturated with water & may be present in free form. For on-line monitoring of water content in transformer oil, sensor is the main part. Sensors used in on-line monitoring of moisture content in oil need to endure

transformer's severe environmental conditions which include the top temperature 100°C and the hottest-spot temperature 145°C. Compared to the traditional humidity-sensitive materials such as acetate fibre, polyimide is a humidity-sensitive material which has a very good heat resistance. Polyimide has stable physical and chemical characteristic from -200°C to 400°C.



Fig 2. Doble Moisture-in-oil Sensor.

When polyimide film capacitive humidity sensor is dropped into the insulating oil, there is a moisture dynamic equilibrium between polyimide film and insulating oil. When moisture content in insulating oil changes, the amount of water molecule absorbed by the polyimide film change accordingly. So the relative permittivity  $\epsilon_r$  of polyimide humidity sensitive film will change. Polyimide film humidity sensor is equivalent to a parallel plate capacitor. Its capacity is defined in equation 4.

$$C = \frac{\epsilon_0 \epsilon_r A \epsilon}{\tau} \quad \text{Equation (4)}$$

Where  $\epsilon_0$  vacuum dielectric is constant,  $A\epsilon$  is effective area of polyimide film and  $\tau$  is thickness of polyimide film. The change of capacity is translated into a signal which microcontroller can recognize through the second test circuit. So on-line monitoring of moisture content in insulating oil is realized.

### B. Off-Line Monitoring

The analysis of moisture in oil performed in the laboratory is performed by Karl Fischer titration described in ASTM Test Method D 1533 or IEC Method 60814. The test setup is shown in the figure 3. It involves a coulometric titration technique involving the reduction of an iodine- containing reagent. The methods are used to determine the amount of water in an oil sample on a weight-to-weight (mg/kg) basis or what is commonly known as ppm (parts per million). Karl Fischer titration is a method in analytical chemistry that determines trace amounts of water in a sample using volumetric or coulometric titration. KF Titration basically adds a reagent of known concentration (iodine) to an unknown substance until the concentrations are balanced together. However, it is greatly affected by several influences: There is always moisture ingress from the atmosphere during the sampling process, transportation and sample preparation in the laboratory. Sometimes direct injection of sample and heating method lead to different results for water content in insulating oil. It serves as a benchmark for other methods such as moisture equilibrium method & dielectric response methods.



Fig 3. KFT Titration Test Setup

#### IV. EXPERIMENT

During transformer operation, partitioning of water content between insulating oil and paper insulation in transformer is depending upon the temperature changes that affect the water solubility properties. The water content during laboratory experiment needs to be stay constant, it means that the laboratory test cell should be free from any hydrophilic materials that may adsorb and absorb water to oil as oil temperature changes during test. Laboratory test setup is shown in Fig. 2. At least two oil samples for KFT water content measurements were taken during test cycle to minimize the error of the KFT water content measurement. PPM value, relative saturation and temperature measurements were carried out on the variety of new and service aged oils, presented in Table III. The seven tested oil samples are well known mineral inhibited transformer oils according to IEEE Std C57.106-2006 specifications.

#### V. RESULTS AND DISCUSSIONS

Sample no. 1, 2 & 3 are taken from the newly installed transformers & sample no. 4, 5, 6, & 7 are taken from the aged transformers. These samples are tested for moisture measurement in the insulating at different temperatures in the laboratory as well as on-line also. The results of these tests are tabulated in the Table III. Using these results of moisture in the transformer oil of different conditions, the moisture content in the paper insulation of the transformer is proposed with the help of equilibrium curves.

In the oil sample 1, 2 & 3 the moisture saturation was measured directly onsite by dole moisture in oil sensor and the moisture content in ppm by the Karl- Fischer titration in the laboratory. An equilibrium diagram based on relative saturation [8] led to 2.3, 2.2 & 2.5 % of moisture in cellulose (RS) that agrees with the KFT analysis of the paper sample. At the same time when the direct application of equilibrium curves that is based on moisture content in insulating oil in ppm, indicated high water content in paper that are 2.9, 2.5 & 2.8 %.

Similarly these calculations were done on the samples 4, 5, 6 & 7 that have been taken from aged transformers. The equilibrium diagram based on relative saturation [8] led to 4.0, 3.1, 3.0 & 1.8 % of moisture in cellulose (RS) that agrees with the KFT analysis of the paper sample. At the same time when the direct application of equilibrium curves that is based on moisture content in insulating oil in ppm, indicated high water content in paper that are 4.4, 3.6, 3.3 & 2.1 %. From this experimental analysis it is clear that on-line monitoring of the moisture in the transformer oil is better than the off-line monitoring.

TABLE III  
RESULTS OF THE WATER CONTENT IN PAPER AND OIL

| No. Of Samples | Temperature (°C) | Water In Oil (PPM) By KFT | Relative Saturation (% RS) By Domino Sensor | Water In Paper (%)                       |   | Error In Measurement (Water in Paper %) |
|----------------|------------------|---------------------------|---|--|---|---|
|                |                  |                           |   | Equilibrium Based On PPM Moisture In Oil | Equilibrium Based On % RS Moisture In Oil |   |
| 1.             | 25               | 8                         | 10.76                                       | 2.9                                      | 2.3                                       | 0.6                                     |
| 2.             | 30               | 10                        | 10.9  | 2.5                                      | 2.2                                       | 0.3                                     |
| 3.             | 40               | 21                        | 15  | 2.8                                      | 2.5                                       | 0.3                                     |
| 4.             | 30               | 25                        | 29  | 4.4                                      | 4.0                                       | 0.4                                     |
| 5.             | 40               | 31                        | 24.2  | 3.6                                      | 3.1                                       | 0.5                                     |
| 6.             | 50               | 45                        | 24.5  | 3.3                                      | 3.0                                       | 0.3                                     |
| 7.             | 70               | 55                        | 14  | 2.1                                      | 1.8                                       | 0.3                                     |

## VI. CONCLUSION

The main framework of this article has been performed on water content measurement in the transformer oil & prediction of moisture in the paper insulation system of the transformers. Experimental evaluations have been conducted on transformer oil samples of different working transformers for the evaluation of the water content in the transformer insulation system. The obtained results show that temperature variation and the sharing of moisture between the oil and paper affect the condition of transformers. The results obtained also shows that temperature variation has great influence on the moisture migration between oil-paper insulation systems of the transformer. The experimental results emphasized the online monitoring & off-line monitoring for water content in insulating oil measurements. This aim can be realized by the means insulating oil water content on line & off-line monitoring & their comparisons and the obtained moisture content in the paper using equilibrium curves as it was shown in this paper.

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## REFERENCES

- [1] IEC TC10, IEC 60422 Ed. 3.0 b:2005, Mineral insulating oils in electrical equipment - Supervision and maintenance guidance, Multiple. Distributed through American National Standards Institute (ANSI),2007.
- [2] "IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment," IEEE Std C57.106-2006 (Revision of IEEE Std C57.106-2002), 2006.
- [3] V. G. Arakelian, I. Fofana "Water in Oil-Filled High-Voltage Equipment Part II: Water Content as Physicochemical Tools for Insulation Condition Diagnostic", IEEE Trans. Dielectr. Electr. Insul. Vol. 23, No. 5, September/October 2007.
- [4] A. Setayeshmehr, J. Abdallah, A. Akbari, H. Borsi and E. Gockenbach, "Evaluation of water exchange between oil and paper in transformer under operating condition", the 16th International Symposium on High Voltage Engineering Johannesburg, ISH 2009.
- [5] L. E. Lundgaard, W. Hansen, D. Linhjell and T. Painter. "Ageing of Oil Impregnated Paper in Power Transformers." IEEE Transactions on Power Delivery, vol. 19, No. 1, January 2004.

- [6] Y. Du, M. Zahn, B.C. Lesieutre and A.V. Marnishev and S.R. Lindgren "Moisture Equilibrium in Transformer paper-oil systems", IEEE Electr. Insul. Mag., Vol. 15, No. 1, 1999.
- [7] T. K. Saha, "Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers", IEEE Trans. Dielectr. Electr. Insul. Vol. 10, pp. 903-917, 2003.
- [8] M. Koch: "Reliable Moisture Determination in Power Transformers", Dissertation, IEH, University of Stuttgart, Sierke Verlag Goettingen, Germany, 2008.

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