

Measurements of Moisture Solubility for Differently Conditioned Transformer Oils

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Abstract

It is important to know the moisture solubility of transformer oil in a transformer. It has been reported that transformer oils under different conditions have different solubility. Measurements of solubility for four different types of conditioned oil are presented in this paper: fresh Shell Diala AX oil, lab-aged Shell Diala A oil, Texas Utility used transformer oil, and Ramapo Substation used transformer oil. To avoid the difficulty of achieving full saturation, this paper proposes an alternative method of measuring the moisture solubility in transformer oil using a relative humidity sensor. It utilizes the linearity between the relative humidity of the oil and the moisture content of the oil to indirectly measure the solubility. The measured results of fresh oil, lab-aged oil, and the Texas Utility oil are very close, and only Ramapo oil shows different sensor response characteristics and solubility.

Introduction

Almost all transformers in electric power delivery systems around the world are filled with liquid. The liquid functions both as electrical insulation and as a heat transfer agent. Newer liquids such as silicone and esters have their applications in special-purpose transformers, and with more environmental concerns, there are new alternatives such as edible seed-oil-based fluid [1]. However, the liquid in the majority of transformers is petroleum-based insulating mineral oil. Conventional transformer oil is made "by refining a fraction of the hydrocarbons collected during the distillation of a petroleum crude stock" [2].

It is well recognized that moisture in oil has detrimental effects on transformer performance. One important criterion is the water solubility in oil. When the moisture

in oil exceeds the solubility for that temperature, free water will form and can cause electrical breakdown in a high field stressed region. The conventional way to measure water solubility is to make a saturated oil sample and then test the absolute moisture content. To achieve full saturation in transformer oil is difficult, especially at high temperature because of the high solubility. This paper proposes an alternative method of measuring the solubility using a relative humidity sensor.

There is a general perception that oil under different aging conditions has different solubility. It is important to know the level of accuracy of this general claim, which in turn determines if extra precautions are necessary. Verification was carried out for four differently conditioned oils.

Water Solubility and Relative Humidity Meter

One way of determining water solubility is by the use of the new ASTM Standard Test Method D 4056-92 [3]. This method estimates the solubility of water in hydrocarbons at different temperatures based on calculations from values for density, refractive index, and molecular weight. This is not a very practical way to measure the water solubility. A more conventional way is to make a saturated oil sample and then measure the absolute moisture content using the standard test method for measuring water in transformer oil, the ASTM D 1533 test method known as the Karl Fischer reaction method [4]. To achieve full saturation in transformer oil is not a trivial task, especially at high temperature because of the increasing solubility. Shown in Table 1 are the solubilities of moisture in Shell Diala A oil at different temperatures [5]. The moisture solubility can be expressed in Arrhenius form as

$$\log W_s = A - \frac{B}{T}, \quad (1)$$

Temperature	Water Solubility, ppm
0°C (32°F)	20
15°C (60°F)	45
38°C (100°F)	115
66°C (150°F)	295
82°C (180°F)	500

Table 1: Water solubility of Shell Diala A Oil [5].

where W_s is the saturation solubility of water in oil in ppm and T is the temperature in °Kelvin. For Shell Diala A oil, the fitted A is 7.3 and B is 1630.

Two ways have been generally adopted for making saturated solutions: 1. Bubble moist air through the oil. We found it difficult to achieve saturation at high temperature using this method without a well designed system like that shown in the Appendix of [6]. 2. Directly add free water. One improper practice is simply adding an excess amount of water to a sample, shake it up, and let stand for overnight and then measure water concentration. It is not an acceptable way of measuring the solubility because the diffusion process in the oil is very slow, and letting the solution stand overnight does not guarantee full dissolution. Also, excess free water in the oil will cause an erroneous measurement of water solubility, i.e. the free water might be sampled and measured as water dissolved in oil. Even though water is heavier than the oil, small water bubbles can still exist near the upper body of the oil by surface tension. The measurement results of such samples are non-repeatable and inconsistent. The proper implementation of this method is to add water and mix well until free water is observed. The mixture should be centrifuged to remove any entrained water and then decanted. The correct implementation of both methods requires extra equipment and care.

To avoid the error caused by taking the moisture value of a non-saturated solution as solubility, or solution with excessive free water, an alternative easily implemented method is proposed for measuring moisture solubility in transformer oil. The linearity between the relative humidity of the oil and the moisture content of the oil is utilized to find the solubility:

$$W_c = W_s \times R.H.(%) / 100, \quad (2)$$

where W_c is the water concentration in ppm at temperature T , and W_s is the water solubility in ppm at the same temperature T . By measuring the slope of the curve of *Moisture Concentration versus Relative Humidity*, or the intercept of the curve at R.H.=100%, one can find the

water solubility instead of trying to directly measure the moisture content at 100% relative humidity.

The Mitsubishi Moisture Meter Model CA-05, based on microprocessor controlled Coulometric Karl Fisher titrimetry, is used to measure the absolute moisture content in oil. The commercially available Harley Moisture Sensor is used to measure the relative humidity of transformer oil. Figure 1 shows the Harley CT-880-S moisture sensor used in this investigation. It consists of a dual sensor [7]- a full range (0-100% RH) thin-film capacitive humidity sensor and a thin-film platinum RTD temperature sensor, combined with a linearized 4 to 20 mA, two-wire current transmitter. The unit transmits a 4-20 mA current signal for a moisture range of 0-100% saturation. The temperature corrected current output is converted into equivalent DC voltage output across an externally connected load resistor. The newly shipped sensor was calibrated in fresh Shell Diala AX oil shown in Figure 2. The titration results are obtained by dividing the moisture content by the solubility of the Shell Diala AX oil at that temperature. The reported solubility value of Shell Diala AX oil [5] is used for calibration. The ideal relative humidity is obtained by converting the output voltage by ideal transfer function $R.H.(%) = [(V - I_{min} * R) / 4] * 100%$, where I_{min} is $4 \times 10^{-3} A$ and R is 250Ω . After two years of use in hot transformer oil in our laboratory apparatus, the sensor was recalibrated as shown in Figure 3. By calibration, the relative humidity of the oil is related to the measured sensor output voltage by

$$R.H.(%) = 22.005 \times (V - V_{min}) - 1.308, \quad (3)$$

where V_{min} is 1.06V for the calibrated sensor. The calibration indicates a very good linear relationship between sensor output and the relative humidity.

Differently Conditioned Oils

The measurements are taken for four types of differently conditioned oils at 35°C: fresh Shell Diala AX oil, lab-aged Shell Diala A oil, Texas Utility used transformer oil, and Ramapo Substation used transformer oil. The Shell Diala A oil is Type I oil which is intended for use where normal oxidation resistance is required. Shell Diala AX oil is Type II oil, for more severe service applications requiring greater oxidation resistance. It contains approximately 0.2%w (2000 ppm) of oxidation inhibitor. The lab-aged oil is prepared by heating new oil at 70°C for two weeks with a mixture of moisture and oxygen because heat, moisture and oxygen are the major aging factors. The oil is circulated within an open vessel by a pump for thorough mixing. The Texas Utility oil

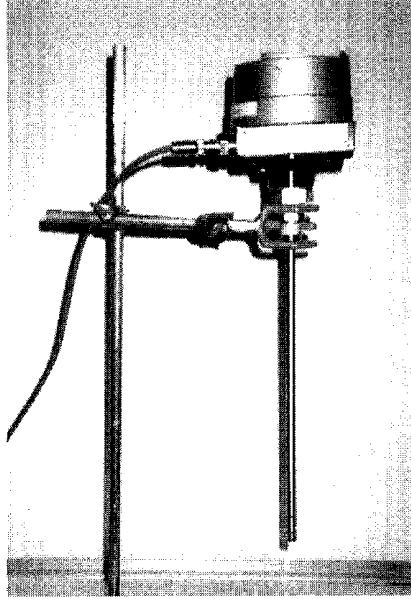


Figure 1: Harley CT-800 moisture sensor. The sensing element is at the bottom of the long rod.

was taken from a transformer that was in service at Texas Utilities. The Ramapo oil is taken from a 500/345kV, 1000 MVA transformer at the Ramapo Substation that experienced failure due to static electrification. Because of the small quantity of oil available, the tested Ramapo oil is a mixture of 80% Ramapo original oil and 20% of new Shell Diala A oil.

Measurement Results

The oil is contained in a 1000 ml kettle. It is well mixed by a magnetic stirrer and the temperature is controlled by an Omega temperature probe and controller. The moisture is bubbled into the kettle by flowing a constant air flow through a flask of deionized water.

The measured oil solubilities and conductivities are listed in Table 2 and the curves are shown in Figure 4. The conductivities of the oils are measured by a gapped tuning capacitor.

Discussion

The results obtained with fresh oil, lab-aged oil, and the Texas Utility oil are very close, whereas the result for Ramapo oil is very different from the rest. Lab tests show the Ramapo oil is not very aged, however, an erratic power factor is measured. There might be contaminants or moist particles in the Ramapo oil that cause the

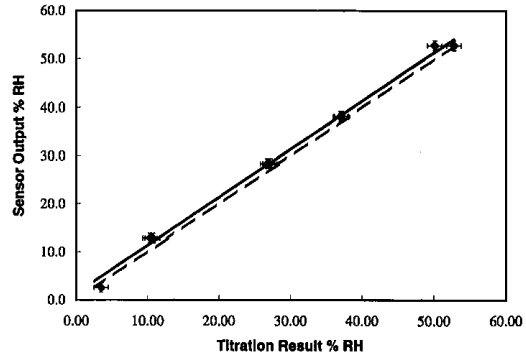


Figure 2: Harley Moisture Sensor calibrated in Shell Diala AX oil at 35 °C when first arrived (calibrated by D. E. Schlicker at MIT High Voltage Research Lab.) The dashed line is the ideal output and solid line is the linear regression of measured output.

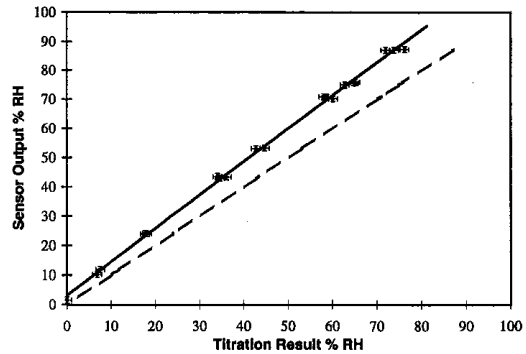


Figure 3: Harley Moisture Sensor calibrated in Shell Diala AX oil at 35 °C after two years in service. The dashed line is the ideal output and solid line is the linear regression of measured output.

observed moisture sensor response. Indeed Golovan' et al [8] also observed that the increase of polar impurities in the oil "leads to a significant increase in oil hygroscopicity and a breakdown of the linear relationship between the water uptake capacity and the relative humidity of the air". This observation also serves as a caution for using the moisture sensor in contaminated oil. Because of the nonlinear behavior of the sensor output, the predicted value of solubility of Ramapo oil is only a rough estimation. The proposed method is effective only when the sensor response is linear. Another possibility is that the contaminants in the oil could affect the chemical reaction process of the Karl Fisher titration and cause a false reading.

Griffin *et al.* at Doble Engineering Company [6] extensively studied moisture solubility in mineral oils. From

Oil Type	Fresh Shell Diala A [5]	Lab-Aged Shell	Texas Utility	Ramapo
Solubility (ppm), 35°C	102	104	108	142
Conductivity (pS/m)	0.7 (35°C)	7.2 (70°C)	9.5(35°C)	10.1(35°C)

Table 2: Comparison of measured water solubility at 35°C and conductivity in differently conditioned oils.

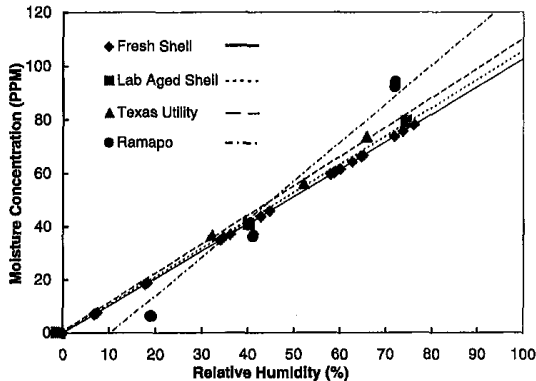


Figure 4: Measurements of moisture concentration versus the relative humidity for differently conditioned oils at 35°C.

their measurements of ten in-service aged oils and two oils with accelerated oxidation in the laboratory, they concluded that: "oils which are in serviceable condition show little change in their water solubility characteristics. Only when the oil is severely aged or contaminated would the solubility be expected to increase significantly." Our results agree with Doble's conclusion.

Conclusion

Water solubility is one of the important parameters of transformer insulation. A measurement technique utilizing the linearity between the relative humidity of the oil and the moisture content of the oil to indirectly measure the solubility is proposed. It avoids the difficulty of achieving full saturation of the test sample and associated errors. However, it can give the correct solubility only when the sensor response maintains linearity. Results of differently aged oils show that normal operation under service temperature is less likely to significantly change the water solubility. This agrees with Griffin's results [6].

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References

- [1] "Transformers use edible seed-oil-based fluid," *IEEE Power Engineering Review*, vol. 19, p. 34, Feb. 1999.
- [2] T. O. Rouse, "Mineral insulating oil in transformers," *Electrical Insulation Magazine*, vol. 14, no. 3, pp. 6-16, 1998.
- [3] "Standard test methods for estimation of solubility of water in hydrocarbon and aliphatic ester lubricants (ASTM D 4056-92(1997))." *Annual Book of ASTM Standards*, 05.02, 1998.
- [4] "Standard test methods for water in insulating liquids (Karl Fischer reaction method (ASTM D 1533-86))." *Annual Book of ASTM Standards*, 10.03, 1987.
- [5] Shell Oil Company, One Shell Plaza, 900 Louisiana Street, Houston, Texas 77002, (800) 231-6950, *Shell Diala Oils*. Shell Lubricants Technical Bulletin SOC: 39-92.
- [6] P. Griffin, C. Bruce, and J. Christie, "Comparison of water equilibrium in silicone and mineral oil transformers," in *Minutes of the Fifty-Fifth Annual International Conference of Doble Clients*, 1988. Paper No. 10-9.
- [7] Harley Moisture Sensor, Model CT-880-BN-H-(0-100%)-X, J.W. Harley Inc., Monitoring Products Group, 9177 Dutton Drive, Twinsburg, OH 44087, (800) 635-3030.
- [8] G. D. Golovan', T. B. Zhilyaev, A. I. Panchenko, and V. S. Kriven'kaya, "Water solubility in transformer oils with various hydrocarbon compositions," *Chemistry and Technology of Fuels and Oils*, vol. 20, no. 8, pp. 387-391, 1984.