Understanding Water in Transformer Systems

The Relationship Between Relative Saturation and Parts per Million (ppm)

by Lance Lewand
Doble Engineering

Water content in transformer oil in parts per million (ppm) is a familiar concept to most in our industry, and limits of 30 to 35 ppm are generally referenced. However, these simple concentration limits have limited value in diagnosing the condition of transformer systems and, thus, the concept of relative saturation (RS) of water in transformer oil has been re-introduced over the past 15 years. The concept of relative saturation of water in transformer oil is not a new one and was originally championed by Frank Doble as early as the mid 1940s.Thus, this article discusses and details the relationship between RS and ppm.

It is well known that moisture continues to be a major cause of problems in transformers and a limitation to their operation. Particularly problematic is excessive moisture in transformer systems, as it affects both solid and liquid insulation with the water in each being interrelated. Water affects the dielectric breakdown strength of the insulation, the temperature at which water vapor bubbles are formed, and the aging rate of the insulating materials. In the extreme case, transformers can fail because of excessive water in the insulation. The dielectric breakdown strength of the paper insulation decreases substantially when its water content rises above two to three percent by weight. Similarly, the dielectric breakdown voltage of the oil is also affected by the relative saturation (RS) of water in oil. The maximum loading that is possible while retaining reliable operation (i.e., preventing the formation of water vapor bubbles) is a function of the insulation water content. For example, dry transformers (<0.5 percent water in paper) are much less susceptible to water bubble evolution. In this case, emergency loading at hot-spot temperatures below 180°C may be possible with little risk of bubble formation. In contrast, a wetter transformer, with 2.0 percent moisture in the paper, runs the risk of water bubble formation with hot-spot temperatures as low as 139°C under the same conditions. A more long-term problem is that excessive moisture accelerates the aging of the paper insulation, with the aging rate being directly proportional to the water content. For example, as the water content in the paper doubles so does the aging rate of the paper. The deterioration of the paper insulation results from the weakening of the hydrogen bonds of the molecular chains of the paper fibers. For these reasons it is important to have a means of assessing the moisture content of transformer systems and to maintain transformers in a reasonably dry state.

In order to fully understand water and its dynamics in transformer systems, a short explanation of the different types of water encountered and the concepts of solubility and relative saturation are provided.

Types of Water in Oil

Water can exist in several different states within the transformer. There are three basic types of water found associated with transformer oil:

- 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.

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

What is Water in Oil (ppm), Solubility of Water in Oil, and RS of Water in Oil?

The detection of water in oil performed in the laboratory is most often performed by an analytical technique called Karl Fischer titration described in ASTM Test Method D 1533 or IEC Method 60814. Both methods are very comparable and involve 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).

The concepts of solubility and relative saturation can sometimes be difficult to understand, but it is an important concept when trying to assess the dryness or wetness of a transformer system. **Solubility** is defined as the total amount of water than can be dissolved in the oil at a specific temperature. The solubility of water is not constant in oil but changes due to temperature. As the temperature increases, the amount of water that can be dissolved in oil also increases. The increase is not linear but exponential in function. For example, at 10°C only 36 ppm of water can be dissolved in the oil, whereas when the temperature increases to 90°C, the amount of water that can be dissolved in the oil increases tremendously to almost 600 ppm. The table shown lists the calculated solubility limits for oil at various temperatures. These levels are the greatest amount of water that can be dissolved at the temperatures listed. If the concentration of water in oil is greater than that shown for that specific temperature then, in all likelihood, the oil is supersaturated with water, and free or emulsified water could exist.

Table 1 — Water in Oil Solubility as a Function of Temperature

Oil Temperature	Water Content in Oil, ppm
0°C	22
10°C	36
20°C	55
30°C	83
40°C	121
50°C	173
60°C	242
70°C	331
80°C	446
90°C	592
100°C	772

The solubility for mineral oil can be calculated using Equation 1:

(Equation 1) $\text{Log } S_o = -1567/K + 7.0895$

Where: S_o is the solubility of water in mineral oil
K is the temperature in Kelvin (°C + 273)

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

(Equation 2) $RS = W_c / S_o \ (100\%)$

Where: W_c is in ppm wt./wt.
S_o is in ppm wt./wt.

For example, a sample of oil was taken for determination of the water content. The temperature of the oil at the time of sampling was 62°C. The laboratory performed the analysis and determined the water content to be 11 ppm. From Equation 1, it is calculated that the solubility level at 62°C is 259 ppm. As discussed previously, relative saturation is the actual measured value compared to the solubility value. In this case it is 11 ppm divided by 259 ppm resulting in a relative saturation of 4.25 percent.

Effects of Relative Saturation on Dielectric Strength

To properly maintain and operate transformers, an understanding of the effects of moisture on the dielectric breakdown strength of the electrical insulating liquids is necessary. Increasing moisture content reduces the dielectric breakdown voltage of insulating liquids. The correlation between the water content in new, filtered, mineral oils at room temperature and the dielectric breakdown voltage using ASTM method D 1816 (0.04 inch gap) is given in Figure 1 (water content, ppm). Of course, the dielectric breakdown voltage is also a function of the number and type of particles and their conductivity, not just the water content.

Taking the same dielectric breakdown voltage data and converting it to RS (Figure 1, %RS graph) provides a much straighter curve except at the extremes. It is evident that there is a better correlation between RS and dielectric breakdown voltage than with moisture concentration and dielectric breakdown voltage.

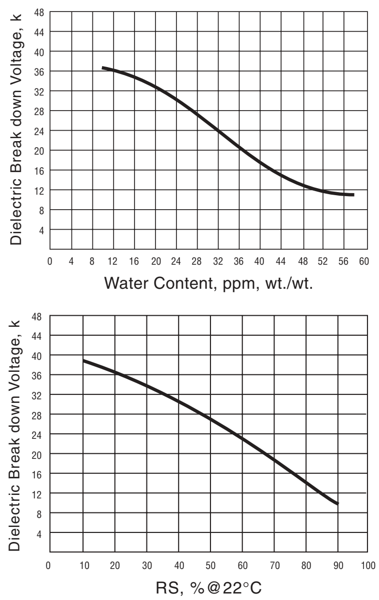

Figure 1— Dielectric Strength Versus Water Content and Relative Saturation (RS)

A simple example illustrates that the dielectric breakdown voltage of insulating oils is proportional to the relative saturation of water in oil rather than the concentration in ppm. The humidity is controlled in this example so the concentration of water is held constant at 30 ppm. The first dielectric breakdown measurement is made at 100°C. At this temperature the solubility of water in oil is about 772 ppm (Table 1). The relative saturation of water in oil is therefore about four percent (30 ppm/772 ppm x 100), and the dielectric breakdown voltage of a well-filtered oil would be quite high. The temperature is now reduced to room temperature or about 22°C. The solubility of water in oil is about 60 ppm (Table 1), and the relative saturation is 50 percent.

The dielectric breakdown voltage would be expected to be about half of what it was when the relative saturation was very low. If the temperature is cooled to 0°C, the results of a dielectric breakdown voltage should be quite low because the solubility of water in oil at this temperature is about 22 ppm (Table 1). As the water content in the oil is higher than this, the water forms an emulsion and begins to condense. During all this time the concentration of water in oil has not changed. This relationship is shown in Figure 2.

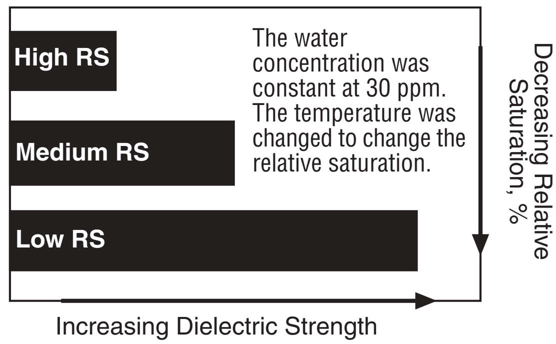

Figure 2 — Relationship between Dielectric Strength and RS

Transformers are more complicated systems than this simple example. However, the same basic principles apply for the dielectric breakdown strength of the liquid dielectric. That is, it remains a function of the relative saturation of water in the oil. During the cool-down cycle of a thermal transient in a transformer some of the moisture returns to the paper and some of the moisture remains in the oil. The relative saturation of water remaining in the oil will influence its dielectric breakdown voltage.

What Does This All Mean for a Transformer System?

Water does not remain at the same concentration in insulations but, rather, it is continuously migrating between the solid and liquid insulation. In order to understand the significance of the water-in-oil value, the operating temperature of the transformer at the time of sampling must be known. Most of the water in a transformer system resides in the solid insulation (paper and pressboard) and not in the oil. As temperature increases the water is forced from the paper into the oil. Although the amount of water in the paper will change relatively little, the concentration in the oil may change by an order of magnitude or more, depending upon the initial water content of the paper and the temperature increase. Fortunately, as described previously, the solubility of water in oil increases with temperature such that the relative saturation may not change much under such conditions, even though the absolute water values in ppm can increase tremendously. In fact, the normal suggested limits of 30 to 35 ppm may be indicative of a wet transformer if the insulation was at equilibrium at temperatures of 25°C or below since this represents a relative saturation of 50 percent or greater in the oil. To maintain reasonable dielectric breakdown strength of oil, it should remain below 50 percent saturation of water in oil.

References

Doble, F. "The Doble Water Extraction Method," *Minutes of the Thirteenth Annual conference of Doble Clients,* 1946, Sec. 10-401.

Griffin, P. J. "Water in Transformers – So What!," *National Grid Condition Monitoring Conference*, May 1996.

Lewand, L. R. and Griffin, P. J., "How to Reduce the Rate of Aging of Transformer Insulation," *NETA World,* Spring 1995, pp. 6-11.

Moser, H.P. "Part II. Aging of Insulating Materials," *Transformerboard*, Special Print of Scientia Electrica, translated by W. Heidemann, EHV-Weidmann Lim., 1979, pp. 12-15.

Griffin, P. J., Bruce, C. M., and Christie, J. D. "Comparison of Water Equilibrium in Silicone and Mineral Oil Transformers," *Minutes of the Fifty-Fifth Annual International Conference of Doble Clients*, 1988, Sec. 10-9.1.

Lance Lewand received his BS degree at St. Mary's College of Maryland in 1980. He has been employed by the Doble Engineering Company for the past seven years and is currently Project Manager of Research in the materials laboratory and Product Manager for the DOMINO™ product line. Prior to his present position at Doble, he was the Manager of the Transformer Fluid Test Laboratory and PCB and Oil Services at MET Electrical Testing in Baltimore, MD. Mr. Lewand is a member of ASTM committee D 27.