The Effect of Moisture Sensor Location on Reliable Transformer Oil Monitoring

Study of Water Diffusion in Stagnant Oil

Power transformers are among the most valuable and important assets in electrical power networks, and moisture is one of the key factors impacting the operational performance of transformer oil. Traditionally, the moisture content of oil has been determined using laboratory analysis of oil samples, but on-line monitoring is becoming increasingly popular. This is due to the fact that it provides real-time data that enables early fault detection, allowing the operator to take timely corrective actions before a problem can escalate.

Figure 1. Test setup.

In this study we examined water diffusion in stagnant oil in order to predict the increase in moisture sensor response time due to unfavorable choice of installation location. We also discuss where is the optimal location for moisture sensor so that measurement is representative of the oil condition within the transformer.

Method

Figure 1 shows the test setup used in this study. It consists of two Vaisala MMT318 transmitters that measure oil moisture and temperature at two different locations. One transmitter (the probe shown on the left side of the picture) is installed in a side tube where oil does not flow and moisture is transferred through diffusion. The second transmitter (shown on the right of Figure 1) is installed in the main line, directly into the oil flow. The first probe is used to determine the water diffusion coefficient outside the oil flow and the second acts as a reference probe inside the oil flow.

In the beginning of the test, the oil circulating in the test setup (see the schematic in Figure 2) is first dried using nitrogen flow and the side tube is filled with dry oil. Then the oil flow to the measurement line is closed and the oil is directed to bypass the transmitters through a separate line. This means that the oil in the measurement line remains dry, while moisture is added to the oil circulating in the rest of the setup. Finally, the moist oil flow is directed to flow through the measurement line and relative saturation and temperature readings of the two MMT318 transmitters are logged until moisture has reached its final level. The test is carried out three times, with the sensor head of the transmitter installed into the side tube at distances of 17.3 cm, 6.3 cm, and 3.7 cm from the measurement line.

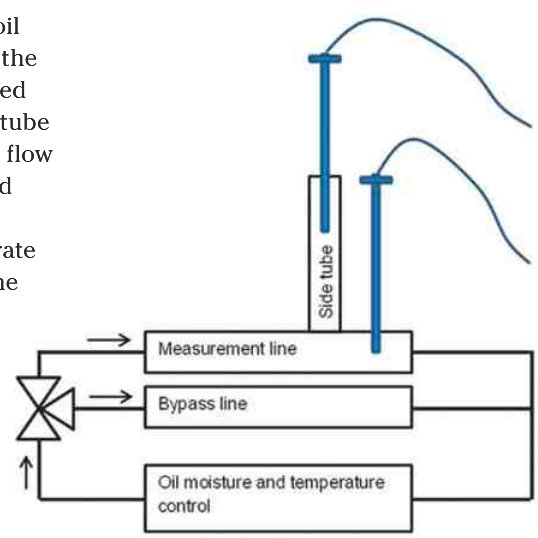

Figure 2. Test setup schematic.

Findings

The relative saturations measured by the two transmitters located in the side tube (RS_{diff}) and in the oil flow (RS_{ref}), as well as a curve fitted to RS_{diff} (named RS_{fit}), are shown in Figures 3 to 5 for the three test runs described above. Figure 3 shows the results of the test run where the sensor is located at a distance of 17.3 cm from the oil flow, while Figures 4 and 5 show the results for the distances of 6.3 and 3.7 cm respectively. When examining RS_{ref}, it can be seen that the readings increase slowly at first and then more rapidly. The slow increase corresponds with the situation where the oil flow to the measurement line is closed and moisture is added to the oil circulating through the rest of the setup. This small leakage does not have any bearing on the conclusions of this study. The rapid change in RS_{ref} begins when the moist oil flow is again directed through the measurement line. The fitted curve RS_{fit} is given by the equation

$$RS_{fit}(t) = (RS_{max} - RS_0)(1 - e^{-(t-t_0)/\tau}) + RS_0 \quad (1)$$

where RS_{max} and RS_0 are the final and initial relative saturation levels, respectively, t_0 is the time lag during which the moist oil is directed through the measurement line but diffused water is not yet detected in the side tube, and τ is the response time constant. Table 1 summarizes the parameters of best fits of Equation (1) to the measured data.

The diffusion coefficient D, when assumed constant, is given by the equation

$$D = \frac{X^2}{6t_0}, \quad (2)$$

where X is the diffusion length and t_0 is the diffusion time lag [1,2]. Using Equation (2) and the distance and time lag data from Table 1 yields a consistent value of $D = (1.4 \pm 0.2) \cdot 10^{-4}\ cm^2/s$.

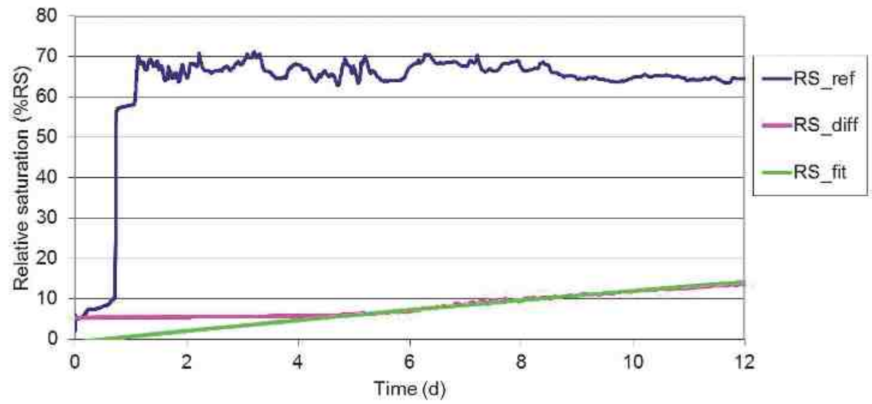

Figure 3. Relative saturation in the measurement line (RS_{ref}) and in the side tube (RS_{diff}), and best fit of Equation 1 to RS_{diff} (named RS_{fit}). Distance from sensor head to oil flow is 17.3 cm.

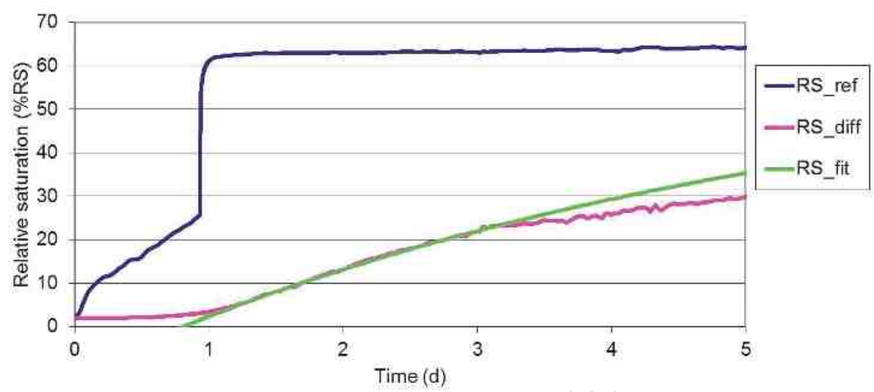

Figure 4. Relative saturation in the measurement line (RS_{ref}) and in the side tube (RS_{diff}), and best fit of Equation 1 to RS_{diff} (named RS_{fit}). Distance from sensor head to oil flow is 6.3 cm.

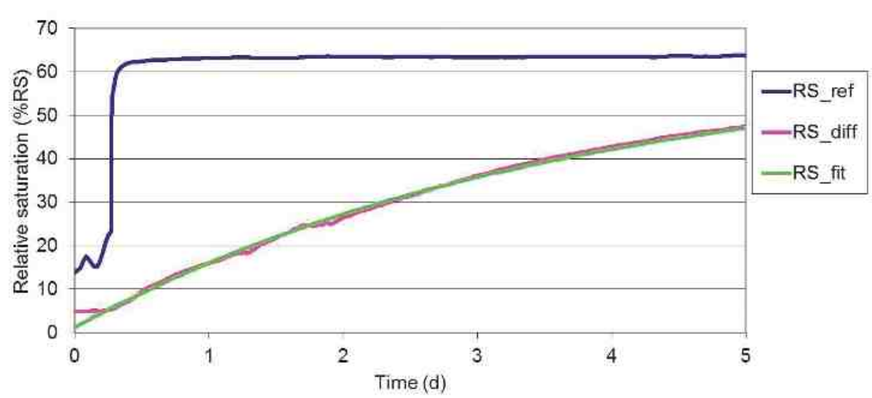

Figure 5. Relative saturation in the measurement line (RS_{ref}) and in the side tube (RS_{diff}), and best fit of Equation 1 to RS_{diff} (named RS_{fit}). Distance from sensor head to oil flow is 3.7 cm.

The tests carried out in this study demonstrate that the response time of a moisture sensor located in a side tube outside the oil flow increases rapidly as the distance of the sensor from the oil flow is increased. When examining Table 1 and Figure 6 it can be seen that a distance of just a few centimeters (3 to 6 cm) corresponds to a response time constant of several days (3 to 5 days), which is impractical from the viewpoint of moisture measurement. The diffusion time lag must also be taken into account, as this also increases as the sensor distance from the oil flow is increased (see Figure 7), further extending the response time of moisture measurement.

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Distance from oil flow (cm)	Diffusion time lag t_0 (d)	Response time constant τ (d)	Diffusion coefficient D (cm^2/s)
17.3	4.6	45	$1.3 \cdot 10^{-4}$
6.3	0.5	5.1	$1.5 \cdot 10^{-4}$
3.7	0.2	3.6	$1.3 \cdot 10^{-4}$

Table 1. Summary of test results.

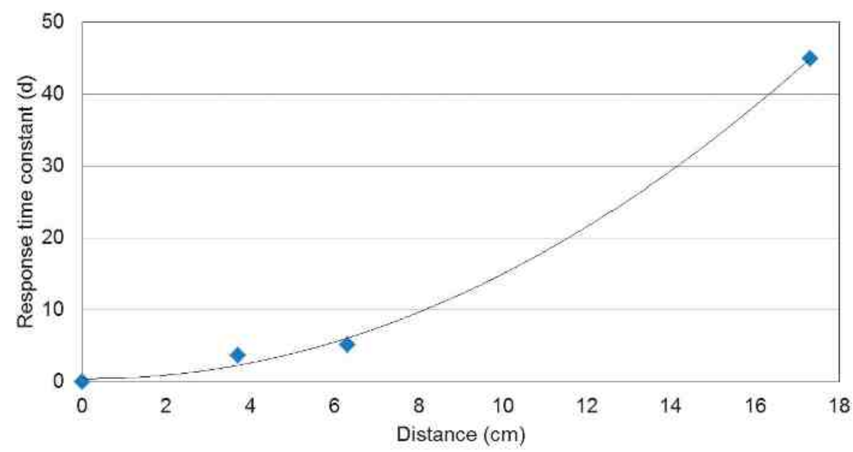

Figure 6. Response time constant τ versus moisture sensor distance from oil flow.

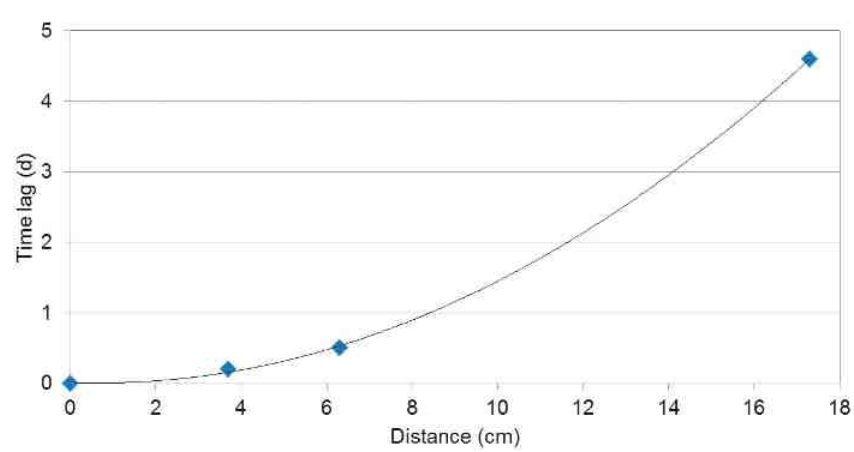

Figure 7. Diffusion time lag t_0 versus moisture sensor distance from oil flow.

Conclusions – Location the Key to Accurate Measurement

The results of this study show that the response time is very long in stagnant oil. Furthermore, it is uncertain whether the relative saturation at the sensor level will ever reach the relative saturation of the flowing oil. Therefore, it is clear that the moisture sensor should be placed directly into the oil flow. This provides direct contact with oil that is truly representative of the oil condition within the transformer.

The oil cooling circulation line of a transformer provides an installation location where true oil exchange is present and where the oil flow significantly reduces the sensor's response time, meaning that the measured values are representative and provided in real time. Where installation to optimal location is not possible, it is strongly recommended to minimize the distance between the sensor and the oil flow. The sensor should not be located at the bottom of the transformer tank unless it is evident that there is true oil exchange present – the lack of oil flow at the bottom of the tank may mean that the sensor is measuring still sludge and not the actual state of the transformer oil.

Figure 8. Recommended installation locations for the moisture sensor. The oil cooling circulation line (left) is the ideal location for measurement in both forced and free circulation cooling implementations; installation through outer wall of transformer tank (right).

Figure 9. Non-recommended installation locations for the moisture sensor. Oil sample connector near the bottom of the transformer tank (left); expansion tank (right).

References

1) Frisch, H. L. The time lag in diffusion. J. Phys. Chem. 1957, 61; pp. 93–95.
2) Crank, J. Methods of measurement. In: Diffusion in Polymers; J. Crank and G. S. Park, Eds.; Academic Press, New York, 1968; pp. 1–39.