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An Immersible Relative Saturation Moisture Sensor with Application to Transformer Oil

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Abstract

Two polyimide-based capacitive humidity sensors, manufactured by Leeds & Northrup, were calibrated in Shell Diala A transformer oil and 10 cSt silicone oil at 35, 50, and 70°C. The moisture content of the oils was found to be a linear function of the output voltage with the slope increasing with temperature. Thus, the sensitivity of the sensors to changes in the absolute moisture content of the oils was found to decrease with increasing temperature. For transformer oil the sensitivity changed from 30 mV/ppm at 35°C to 9 mV/ppm at 70°C; for silicone oil the sensitivity changed from 10 mV/ppm at 35°C to 4 mV/ppm at 70°C. For a 1 mV resolution in the output voltage, this corresponds to a change in moisture content resolution from 0.03 ppm at 35°C to 0.1 ppm at 70°C for transformer oil and from 0.1 ppm at 35°C to 0.25 ppm at 70°C for silicone oil.

Normalization of the absolute moisture content to the saturation level of moisture in the oil for all three calibration temperatures and both oils demonstrated that the sensors respond to the relative saturation of moisture in the oil. The relative saturation was found to be a linear function of the output voltage. The saturation level of moisture in the oils was measured for the three calibration temperatures and could be expressed in Arrhenius form with an activation energy of 0.317 eV for transformer oil and 0.231 eV for silicone oil. The usefulness of a relative saturation measurement for discerning anomalous behavior in power apparatus is described.

1 Introduction

The reliability of power transformers depends on the accurate measurement of critical parameters that describe the state of the insulation. One important parameter is the moisture content of the circulating oil and the solid insulation. The migration of a minute amount of moisture has been associated with flow electrification at pressboard/oil interfaces [1] as well as the formation of gas bubbles in the oil [2]. Although equilibrium data [3, 4] is used to predict the moisture content of the solid insulation from measurements of the moisture content of the oil, analysis of the mass-transfer time constants in view of the load cycles of a typical large substation power transformer indicate that the transformer is never in moisture equilibrium [5]. Nonetheless, comparison of the measured moisture content with that predicted from dynamic or quasi-stationary adaptive models can provide information about the incipience of anomalous behavior in the transformer [6]. The ability to continuously measure the moisture content of the circulating oil in a transformer can thus prevent catastrophic failures that may not be avoided using standard sampling methods.

The difficulty and expense encountered in mounting monitoring equipment in a transformer requires that the sensors be stable and reliable over the lifetime of a transformer or at least over the period between scheduled maintenances. In addition, the sensors need to withstand the harsh operating conditions of a transformer which include a maximum top oil temperature of 100°C with a corresponding maximum hot spot temperature of 140°C [7]. Previous attempts to develop immersible moisture sensors made use of thin-film plasma-deposited bromobenzene whose dielectric properties were found to be sensitive to the moisture content of the oil. Experimental evidence showed that these films acted as semipermeable membranes, acting as barriers to transformer oil but absorbing moisture in proportion to the absolute moisture content of the oil [8]. Unfortunately, the long-term loss of sensitivity rendered the sensor unreliable over periods of months.

Polyimide films form the basis of numerous versions of capacitive humidity sensors [9, 10, 11]. Polyimide has been found to absorb moisture up to 2% of its dry weight [12]. Experimental evidence based on the moisture-induced change in permittivity indicated that the absorbed moisture has a dipole moment nearly equal to that of free water, suggesting that microvoids in the polymeric network dominate the observed absorption phenomena. The high polarizability of the water molecule results in changes in the dielectric constant of up to 30% [13]. The permittivity and moisture uptake were found to be linear functions of the ambient relative humidity. The use of thin-films in the micron range enable sensors to respond with a time constant of seconds. This time constant is dominated by the diffusion of moisture into the polyimide. The diffusion coefficient of moisture in polyimide was measured to be 4×10^{-13} m^2/s at room temperature with an activation energy of 0.33 eV [13]. Along with these characteristics, the stability, high temperature capability, and chemical inertness of polyimide films render them good candidates for use in a transformer environment.

2 Apparatus

For calibration as well as comparison purposes, two polyimide-based capacitive humidity sensors, manufactured by Leeds & Northrup [10] and distributed by HY-CAL Engineering [14], were mounted in a Pyrex^{TM} reaction kettle. The calibration kettle was sealed from the atmosphere and contained approximately one liter of oil which was continuously stirred with a magnetic stirrer. The sensors were mounted without their protective shields to avoid trapped gas bubbles and remained completely immersed during the calibration. The oil was heated by means of heating coils wrapped around the cell and driven by a temperature controller. The temperature of the oil was independently measured using a partial-immersion, mercury-filled glass thermometer accurate to 0.2°C.

To control the moisture content of the oil, a mixture of dry and wet nitrogen was bubbled through the oil as it was being stirred. The wet nitrogen was produced by bubbling dry nitrogen through a wetting flask. The nitrogen mixture was then dispersed into the oil with the help of a porous distributor plate. The moisture content of the oil was measured using a Mitsubishi Moisture Meter, Model CA-05, which uses microprocessor-controlled coulometric Karl Fisher titrimetry. For transformer oil the anode and cathode solutions were Aquamicron A and C respectively. The oil was sampled with a 10 ml glass syringe. The sample size was chosen to insure a maximum uncertainty of 1 ppm based on the precision of the instrument (±3 μg). Each measurement was made with the sensors and the oil in moisture equilibrium. Typical equilibration times were 4, 3, and 2 hours at 35, 50, and 70°C. These times reflect the wetting process of the oil, not the response time of the sensors. The steady state was verified by observing that the output signal from the two sensors did not change over a period of 30 minutes. The moisture sensors provide a 4 to 20 mA output current which was measured as a voltage across a 250 Ω load resistor with an accuracy of 1 mV, which corresponds to a 0.025% change over the 1 to 5 V output range.

3 Calibration

Using the apparatus described above, the sensors were calibrated in transformer oil. Shell Diala A was chosen as an oil representative of insulating fluids used in power transformers. The sensors were calibrated at 35, 50, and 70°C. During the calibration, the temperature was kept constant and the moisture content was varied.

The results of the calibrations are shown in Fig. 1 where the moisture content measured by the moisture meter is plotted as a function of the output voltage for the two sensors. These plots indicate that the moisture content is a linear function of the output voltage and that the slope of the line increases with the temperature of the oil. The increase in slope at elevated temperatures reduces the sensitivity of the sensor to changes in the moisture content of the oil. Based on estimates of the slopes at each temperature, the sensitivity decreased from 30 mV/ppm at 35°C to 9 mV/ppm at 70°C. For a 1 mV resolution in the output voltage, this corresponds to a decrease in moisture content resolution from 0.03 ppm at 35°C to 0.1 ppm at 70°C. The sensitivity of the sensor is thus reduced at temperatures typical of operating transformers. The solid lines drawn represent a least-squares three-parameter fit of the calibration data for each sensor to the expression

$$m_c(V,T) = (a + bV)\,\mathrm{e}^{-T_o/T}$$

with the moisture content m_c measured in ppm, the output voltage V in volts, and the temperature T in kelvin. The estimated values of the parameters a, b, and T_o are listed in Table 1.

Table 1: Estimated calibration parameters for Leeds & Northrup sensors.

	Transformer oil		Silicone oil	
Parameter	Sensor 1	Sensor 2	Sensor 1	Sensor 2
a (10^6 ppm)	−6.115	−8.376	−2.319	−2.479
b (10^6 ppm/V)	5.345	8.059	2.031	2.351
T_o (K)	3706	3826	3089	3130

To discriminate whether the sensors respond to the absolute moisture content or the relative saturation of the oil, the calibration was repeated with 10 cSt silicone oil, which is known to have a higher saturation level than transformer oil. Early in the process of measuring the moisture content of silicone oil with the moisture meter we found that trace amounts of ketones normally present in silicone oil clouded the titration of water in the cell. Through discussions with a Mitsubishi representative, a new set of anode and cathode solutions (Aquamicron AU and CK) was identified to eliminate this problem. The results of the calibration are shown in Fig. 2. Although the calibration was not as extensive as in transformer oil, here too we found that the moisture content was a linear function of the output voltage and that the slope of the line increase with the temperature of the oil. Based on estimates of the slopes at each temperature, the sensitivity for silicone oil decreased from 10 mV/ppm at 35°C to 4 mV/ppm at 70°C, which corresponds to a decrease in moisture content resolution from 0.1 ppm at 35°C to 0.25 ppm at 70°C. Just as for transformer oil, the solid lines drawn represent a least-squares three-parameter fit of the calibration data for each sensor to the expression for the moisture content as a function of the output voltage and the temperature of the system. The estimated values of the parameters a, b, and T_o for silicone oil are listed in Table 1 along side those for transformer oil.

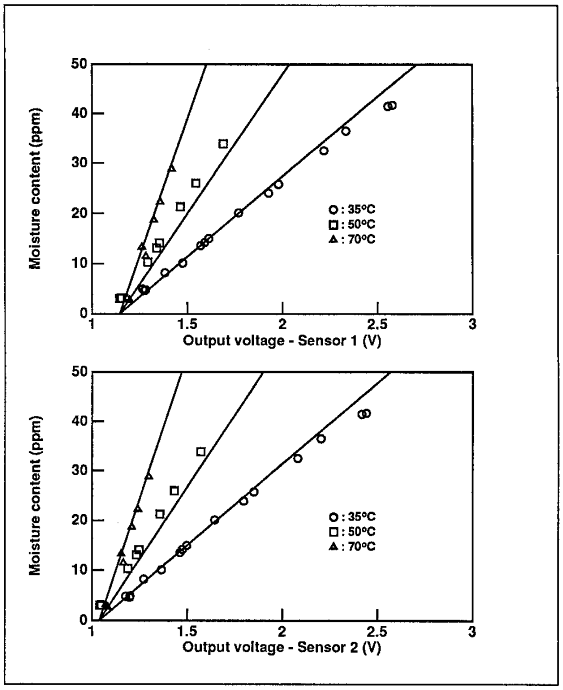

Figure 1: Calibration of the Leeds & Northrup sensors in Shell Diala A transformer oil indicating that the moisture content is a linear function of the output voltage and that the slope of the line increases with the temperature of the oil. The increase in slope at elevated temperatures reduces the sensitivity of the sensor to changes in the moisture content of the oil. The solid lines drawn represent a least-squares three-parameter fit of the data for each sensor to the expression $m_c(V,T) = (a + bV)\,\mathrm{e}^{-T_o/T}$.

4 Relative Saturation

The calibration of the sensors in transformer and silicone oil was motivated not only by the need to correlate the observed signal to the moisture content in the oil, but also by an interest in the thermodynamic nature of the sensors. These experiments help to discriminate whether the sensors respond to the absolute moisture content or the relative saturation of moisture in the oils. Relative saturation rS is defined as the ratio of the absolute moisture content $m_c(T)$ to the saturation level $S(T)$ of moisture in the oil at a given temperature.

$$rS \equiv \frac{m_c(T)}{S(T)}$$

Comparison of the calibration curves for transformer oil and silicone oil, Figs. 1 and 2, shows that for the same moisture content the output voltage generated in transformer oil is greater than that generated in silicone oil at the same temperature. This observation eliminates the possibility that the sensors respond to the absolute moisture content in the oil. If they did, the output voltages in the two cases would have been the same.

To compute the relative saturation of the oils, an independent measurement of the saturation level of moisture in transformer oil and silicone oil was made as a function of temperature. In order to provide an 'infinite' reservoir of moisture for the oil, a 2 cm × 5 cm piece of 1 mm thick EHV-Weidmann Hi-Val pressboard was impregnated under vacuum with deionized water and its surface was padded dry. The piece of pressboard was then attached to the bottom part of the stem of a thermometer which was immersed in a

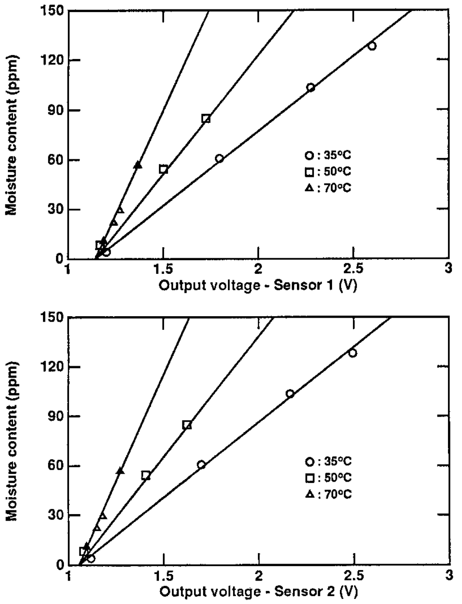

Figure 2: Calibration of the Leeds & Northrup sensors in 10 cSt silicone oil. Just as for transformer oil, the moisture content is a linear function of the output voltage and the slope of the line increases with the temperature of the oil. The solid lines drawn represent a least-squares three-parameter fit of the data for each sensor to the expression $m_c(V,T) = (a + bV)\,e^{-T_o/T}$.

500 ml Erlenmeyer flask full of oil. To insure that the moisture remained dissolved in the oil, all air bubbles were removed and the flask was sealed at the desired temperature. The experiment was allowed to reach equilibrium for 24 hours while a magnetic stirrer provided a means to enhance the mass-transfer process. The flask was then opened and the moisture content of the oil was measured with the moisture meter and the Leeds & Northrup sensors. As the flask was exposed to ambient conditions, the output voltage of the sensors rapidly decreased from the saturation level. No evidence of free water was observed during these experiments. The saturation level of moisture in transformer oil and silicone oil as a function of temperature is shown in the form of an Arrhenius plot in Fig. 3. The solid lines drawn represent a least-squares linear fit of the data to the Arrhenius expression

$$S(T) = S_\infty\, e^{-E_a/kT}$$

with the saturation level $S(T)$ measured in ppm, and the temperature T in kelvin. The constant k is Boltzmann's constant. The estimated values of the parameter S_∞ and the activation energy E_a are listed in Table 2 for transformer oil and silicone oil. These values agree well with those reported in the literature [4, 15].

Table 2: Estimated saturation parameters.

Parameter	Transformer oil	Silicone oil
S_∞ (10^6 ppm)	15.568	1.764
E_a (eV)	0.317	0.231

Using the measured values of the saturation levels, the calibration data shown in Figs. 1 and 2 can be replotted for each sensor in the form of relative saturation as a function of the output voltage. Figure 4 shows the result of this mapping. The fact that the data for all three temperatures and both oils falls on one line demonstrates that the sensors respond to relative saturation. These plots indicate that the relative saturation is a linear function of the output voltage. The solid lines drawn represent a least-squares linear fit of the data for each sensor to the expression

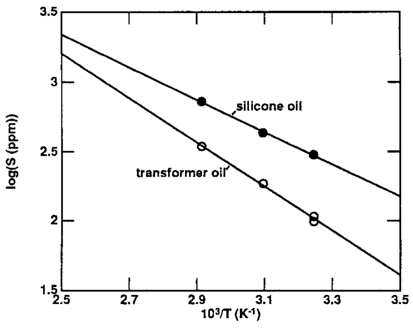

Figure 3: Arrhenius plot of the saturation level of moisture in Shell Diala A transformer oil and 10 cSt silicone oil as a function of temperature. The solid lines drawn represent a least-squares linear fit of the data to the expression $S(T) = S_\infty\, e^{-E_a/kT}$.

$$rS(V) = \frac{m_c(T)}{S(T)} = a' + b'V$$

where the relative saturation rS is a dimensionless number between zero and one, and the voltage V is measured in volts. The estimated values of the parameters a' and b' are listed in Table 3 for both sensors.

Table 3: Estimated relative saturation parameters.

Parameter	Sensor 1	Sensor 2
a'	−0.330	−0.309
b' (V^{-1})	0.297	0.304

5 Conclusions

The sensors have been found to measure the relative saturation of moisture in oil. Thus, the absolute moisture content of the oil can be computed only if the saturation level is known. Alternatively, the sensors can be calibrated in the fluid of interest as a function of temperature. As long as the saturation level of moisture in the oil doesn't change significantly over time, the moisture content of the oil can be reliably measured using these sensors. Experimental evidence indicates that oils which are in serviceable condition show little change in their water solubility characteristics [15]. Accelerated oxidation tests showed similar results. Only when the oil is severely aged or contaminated does the saturation level increase significantly. Polar compounds present in severely aged oils are thought to influence the water solubility characteristics of mineral oils. These compounds are not removed by clay treatment [15].

Present industry practice involves the measurement of the absolute moisture content of the oil. Unless this value is reported with the temperature of the sample, it provides no information about the state of the insulation. It appears therefore that the measurement of interest is the relative saturation rather than the absolute moisture

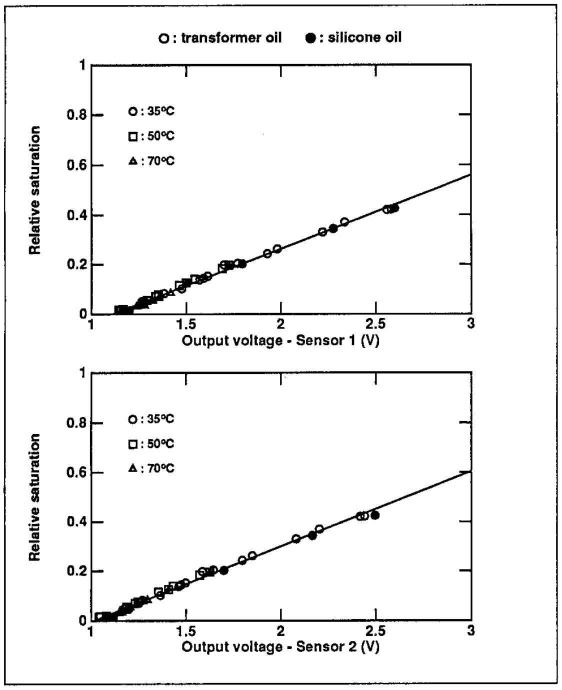

Figure 4: Demonstration that the Leeds & Northrup sensors respond to the relative saturation of the oil. The calibration data for Shell Diala A transformer oil and 10 cSt silicone oil is replotted for each sensor in the form of relative saturation as a function of the output voltage. The fact that the data for all three temperatures and both oils falls on one line demonstrates that the sensors respond to relative saturation. The solid lines drawn represent a least-squares linear fit of the data for each sensor to the expression $rS(V) = m_c(T)/S(T) = a' + b'V$.

content of the oil. Operation of a transformer under conditions in which the relative saturation of moisture in the oil is higher than its equilibrium value can lead to supersaturated oil and consequently the formation of free water. This condition can occur if the temperature of the transformer decreases sufficiently fast that the relative saturation drops below the absolute moisture content of the oil. In this case the excess water may remain dissolved in the oil under supersaturated conditions or nucleate in the form of a water droplet. Knowledge of the absolute moisture content of the oil during the transient would not indicate the incipience of a hazardous condition. The direct measurement by the sensors of the relative saturation of moisture in the oil would therefore provide dynamic information about the health of the transformer.

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