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ON-LINE MOISTURE MONITORING IN TRANSFORMERS AND OIL PROCESSING SYSTEMS

by

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ABSTRACT

An on-line moisture sensor for use in insulating fluids in electrical equipment is described. This sensor uses a high temperature thin polymer film capacitor. Absorption of moisture by the film would increase the dielectric constant of the film. The output of the capacitor is in the 4-20 mA range corresponding to a humidty range of 0-100% RH. The sensor was successfully tested in oil processing systems and transformers up to 80°C. An on-line sensor would be of great value to alert dielectric hazards and to understand moisture transport in electrical equipment.

Key Words : Moisture sensor, transformer oil, monitoring

1. INTRODUCTION

Continuous on-line monitoring of moisture levels in gas and liquid dielectrics is very desirable for electrical equipment. Moisture sensitive thin films have been known for years which change electrical properties such as permittivity and resistivity. Since the 1960s, an aluminum oxide thin film sensor has been in use which responds to vapor pressure of water in the medium to which it is exposed [1]. It is possible to obtain information on the dew point, relative humidity and ppm moisture level from this sensor. Its use is limited by an upper temperature limit of 50°C, need for extensive calibration and slow response.

In the 1980s, researchers used thin film microdielectrometry for moisture sensing in dielectric fluids [2,3]. This required a frequency scan, typically in the 0.01-10,000 Hz range, of the phase angle. An inverted phase peak was observed in these scans, the position of which changed with moisture content. The method was time consuming and required sophisticated equipment. The moistrue calibration curve was found to shift with prolonged use.

In the 1990-91 period, some research work was done on the possible use of thin film capacitive sensors for moisture measurements in dielectric fluids. Such sensors have been available for several years for use in gaseous environments [4]. It was not known whether these sensors would be stable in hot transformer oil and would sense moisture levels typical in transformers. The sensing films used by different manufacturers vary from cellulosic materials to high temperature polymers. Fortunately, it was possible to identify at least one type of film that could withstand hot oil and sense moisture levels [5,6]. The present paper describes the application of such a sensor for on-line use in transformers and oil processing systems.

2. DESCRIPTION OF THE SENSOR

Of the different capacitive sensors tested, the sensor that proved to be useful for the intended application was the one with a high temperature polymer film (polyimide), typically a micrometer thick. The mounting of the film varied from one manufacturer to another. For example, the Ultra-H II™ sensor from Hy-Cal Engineering used an interdigitated electrode mounted on a ceramic substrate. The HUMICAP™ sensor from Vaisala used an upper and lower electrode, with a glass substrate. The Hy-Cal sensor has an outside protective layer of the same polymer, while the HUMICAP sensor's upper electrode acts as a protective layer. These sensors are illustrated in Figure 1. The humidity transmitters which incorporate these sensors are shown in Figure 2. The sensors are mounted at the bottom part of the probe, and they are usually protected by an end cap.

3. MOISTURE SENSOR OUTPUT AND MEASUREMENT

Moisture absorption by polyimide film can be as high as 3.3%, and the dielectric constant(permittivity) would change from 3.0 to 4.0 over the entire range of humidity [7,8]. Moisture absorption is controlled by the relative humidity rather than the absolute moisture content; hence, the sensor would directly measure relative humidity. The output of the sensor is 4-20 mA, corresponding to the humidity range 0-100% in a linear fashion. We may therefore write,

$$\% \text{ RH} = (\text{mA output} - 4) \times 6.25 \qquad (1)$$

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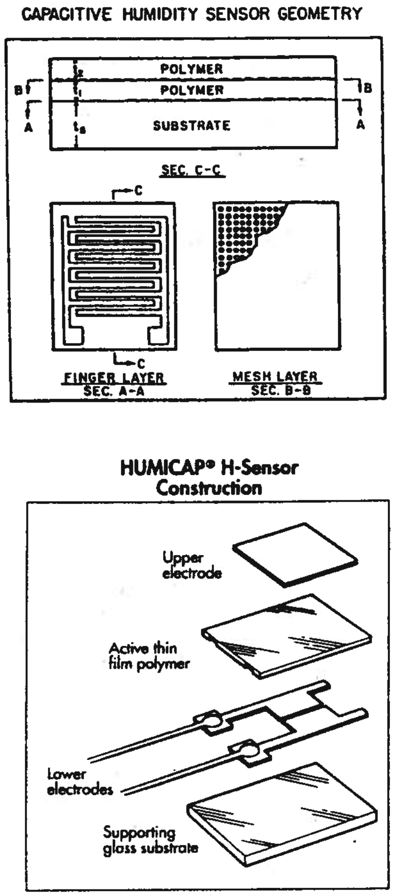

Figure 1. Sensor Geometry
1A. Ultra-H™ Sensor
1B. Humicap™ Sensor

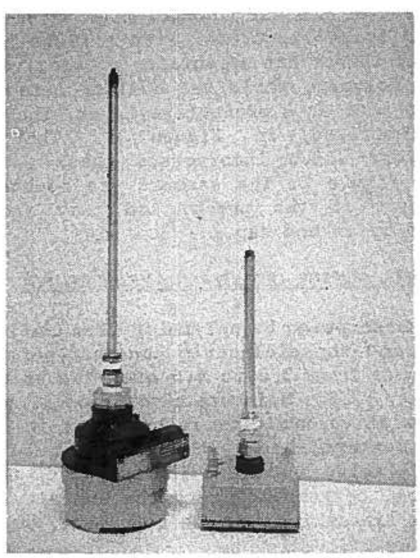

Figure 2. Humidity Transmitters
(Left) Hy-Cal Eng. Model CT 880
(Right)Vaisala Model HMD 20 YB

When used in liquids, the sensor measures relative moisture saturation, rS :

$$\%rS = \frac{\text{moisture content in liquid} \times 100}{\text{moisture saturation value}}$$

$$= (m_c \times 100)/S \qquad (2)$$

$$\text{or} \quad m_c = (\%rS) \times S/100 \qquad (3)$$

where m_c is the moisture content, and S is the water solubility in the liquid at the same temperature (in ppm units). The numerical value of %rS is governed by Eq.(1).

Two types of insulation fluids tested were transformer oil and silicone fluid (50 cSt). The moisture solubility in these fluids are given by:

$$S = A \exp(-E_a/RT) \qquad (4)$$

where E_a is the activation energy, R is the gas constant, T is the absolute temperature, and A is a constant.

The usefulness of Eq.(3) is that from the measured %rS we may compute m_c, the moisture content (usually expressed in ppm units). The parameters in Eq.(4) need to be known. These are given in Table 1 for transformer oil and silicone oil [8]:

Table 1
Typical values of Parameters

Parameter	Transformer oil	Silicone oil
E_a/R	3609	2734
A	12.323×10^6	1.958×10^6

Dielectric fluids differ somewhat in solubility characteristics even for a given type of fluid due to varying composition and aging. It is therefore desirable to generate the above parameters experimentally.

The mA output (or voltage) *vs.* %RH (or %rS) plot should be linear as shown in Figure 3. The 100% rS corresponds to the solubility limit. This plot should be the same for any temperature. On the other hand, the plot of m_c *vs.* %rS changes in slope for different temperatures, as shown in Figure 4. This is due to the temperature dependence on solubility given by Eq.(4). The various plots in Figure 4 can be described by one relationship:

$$m_c = (a + bi)\exp(-c/T) \qquad (5)$$

where i is the mA output; a, b and c are constants. Since the plots meet at the origin, a = 4 mA; if not, it will be slightly higher. Eq.(5) is an alternate form of Eq.(3), and may be used to convert mA output directly to ppm moisture content. Instead of mA output, voltage output may be used with apropriate conversion factor. A still different way of computing m_c is using one of the plots, eg., at 20°C, as reference, and then using a factor to compute m_c at other temperatures, as outlined in Reference [5].

4. PERFORMANCE OF THE SENSOR IN OIL

The moisture sensor performed satisfactorily in hot and cold transformer oil. The temperature range tested was 0-125°C. Above 80°C the sensor could not

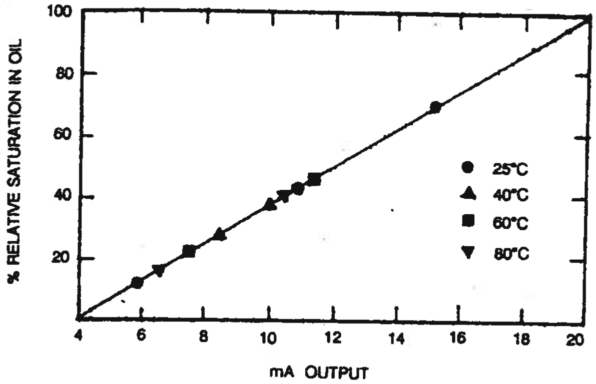

Figure 3. Plot of Relative Moisture Saturation in Oil *vs*. Current Output.

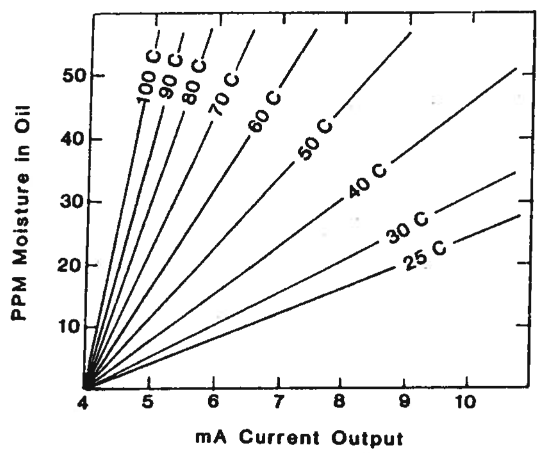

Figure 4. Plots of PPM Moisture Content in Oil *vs*. Current Output

be operated continuously; the sensitivity seemed to decrease with time. Another observation was that though the sensor responded well to a vacuum, when oil was subsequently admitted the sensor did not return to the expected humidity level in a reasonable time. It is preferable to insert the sensor only after vacuum filling. Typical time constant for response in mildly agitated oil was 6 minutes. Nonagitateed oil took hours to reach moisture equilibrium with the sensor. The ideal location of the sensor would be in a flow loop. Since the sensor is used primarily in relatively dry oil, calibration checks should be made at low moisture levels and necessary adjustments should be made.

5. SENSOR APPLICATIONS

5.1 Moisture Monitoring During Oil Filling

Some tests were conducted using a tank of 200L capacity. Oil from a storage drum with 35 ppm moisture was admitted to the tank with a vacuum applied. Figure 5 shows the temperature and %RH changes in the tank before admitting oil. Figure 6 shows the effect of heating the oil after admitting and subsequent shuting off the heat. In this case the ppm moisture does not change, but the %RH changes, becoming lower as the temperature is raised. This is because the moisture saturation limit(S) is higher at higher temperatures; therefore

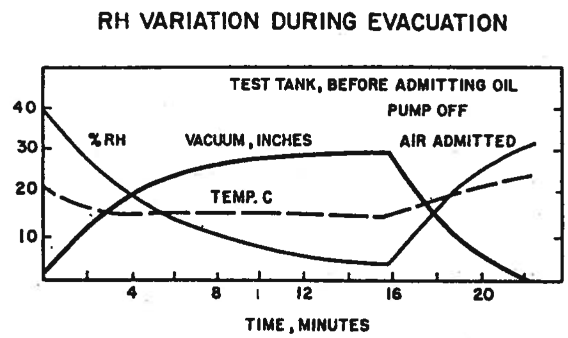

Figure 5. Moisture Sensor Performance During Tank Evacuation.

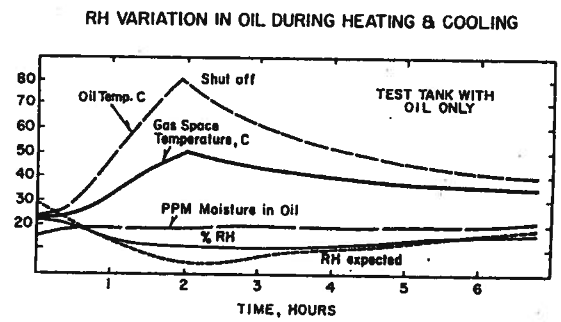

Figure 6. Moisture Sensor Performance During Oil Filling, Heating and Cooling.

relative saturation (rS) decreases. The dashed line is the expected RH curve. The observed RH curve deviated from this probably due to the relatively stagnant condition of the oil.

We have installed a few moisture sensors in our factory oil processing system(Figure 7), the moisture data is collected remotely using a PC.

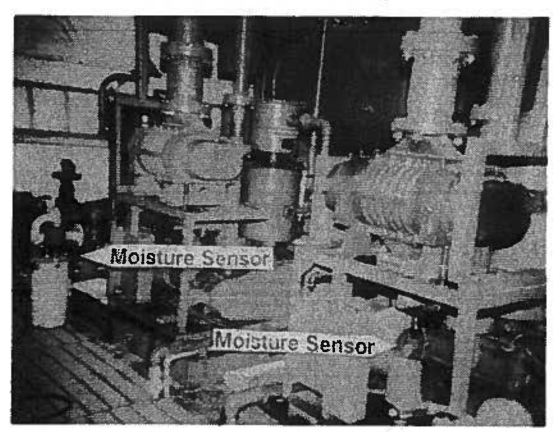

Figure 7. Moisture Monitoring in Factory Oil Processing System

5.2 Transformer Moisture Monitoring

Figure 8 shows the setup used to monitor moisture changes in the oil of a 500 kVA transformer. Figure 9 shows the temperature and moisture profiles during load excursions.

Unlike in Figure 6, the heating and cooling of the oil has a profound effect on the moisture levels. This is because in a transformer we have a paper/oil system. The paper insulation contains over 99% of the total water in the system. Unlike oil, as temperature rises, paper tends to lose moisture. The surrounding oil would take the water lost from the paper; hence, the ppm moisture would rise and would seem to parallel the temperature change. The system would attempt to maintain the same moisture saturation level in oil, and not the same moisture content, at all times. However, when the temperature is rising fast, there is a time lag. As the load becomes constant, the %rS would stabilize. When the load is removed, the temperature would drop, and the excess water in the oil would return to the paper. Again, there is a time lag, so the moisture saturation level would increase in oil for a while since the solubility of water in oil is lower at lower temperatures.

The peak in the moisture saturation curve is to be taken seriously. In subzero winter weather, during load removal the peak may reach 100% saturation. Free water or ice may form under such conditions and the dielectric characteristics of the oil would be degraded. Saturation level, rather than ppm moisture content, is the true indicator of satisfactory moisture level. An on-line moisture sensor would be of great value to prevent failures associated with excessive moisture levels in oil. In the US several utilities have installed moisture sensors for on-line monitoring.

TEST TRANSFORMER FOR MOISTURE MONITORING

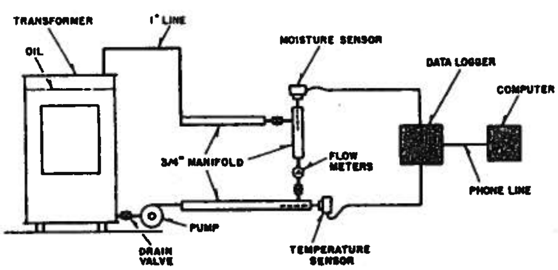

Figure 8. Setup for Moisture Monitoring in a 500 kVA Transformer.

MOISTURE MONITORING IN A TEST TRANSFORMER

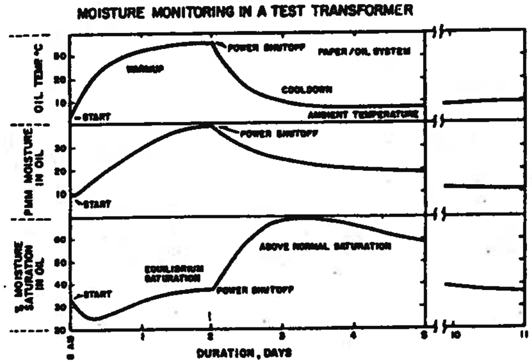

Figure 9. Moisture Monitoring During Transformer Operation.

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RESUME

Le présent article décrit les essais auxquels a été soumis un détecteur capacitif d'humidité à film fin pour mesurer l'humidité dans les fluides isolants. Pour les essais, on a utilisé les transmetteurs d'humidité du commerce. Ces deux transmetteurs utilisent un film polymère haute température pour la détection de l'humidité. L'absorption d'humidité par le film est rapide dans l'air et entraîne un changement significatif de la constante diélectrique. Quand il est utilisé pour des fluides diélectriques, le transmetteur mesure la saturation d'humidité relative. La puissance de l'appareil de mesure va de 4 à 20 mA ce qui correspond à une gamme de 0 à 100% RH. Il est possible de convertir les données de la saturation relative en ppm de teneur en eau en utilisant une relation mathématique impliquant la variabilité avec la température de type Arrhenius.

Les détecteurs ont bien fonctionné dans l'huile du transformateur et dans l'huile de silicone à des températures allant jusqu'à 80°C. Le détecteur a été installé en ligne dans un transformateur de 500 kVA pour une surveillance permanente pendant la mise en route et le fonctionnement. La variation de ppm d'eau dans l'huile du transformateur est à peu près parallèle aux variations de température. La constatation la plus importante a été que lorsque l'unité ne fonctionnait pas, la courbe de saturation relative s'élevait jusqu'à une valeur de pointe puis redescendait progressivement. Cela provient du fait que l'eau dans l'huile ne retourne pas immédiatement vers l'isolation en papier. En hiver, cette valeur de pointe pourrait être suffisamment élevée pour affecter la résistance disruptive de l'huile.

Le détecteur d'humidité a été également testé dans un système de traitement de l'huile en usine. Il est possible de surveiller les changements d'humidité dans l'huile pendant le traitement et le stockage.