Polymer optical fiber moisture sensor based on evanescent-wave scattering to measure humidity in oil-paper insulation in electrical apparatus

Joaquin H. Rodriguez-Rodriguez
Control e Instrumentacion
Instituto de Investigaciones Electricas, IIE
Cuernavaca, Morelos, Mexico
jrr@iie.org.mx

Fernando Martinez-Pinon, Jose A. Alvarez-Chavez
David Jaramillo-Vigueras,
CIITEC - Instituto Politecnico Nacional
Mexico DF, Mexico
jalvarezch@ipn.mx

Abstract—An optical fiber moisture sensor is prepared by coating a 1mm polymer optical fiber with a film 30 micron thick of Polyvinyl Acetate PVA. We have experimentally studied how the light transmission characteristics of such coated optical fiber changes as a function of moisture conditions within an oil-paper insulation, to which the coating is exposed. An optical fiber moisture sensor that can be used to sense moisture present in liquid transformer oil and composite paper insulation in a wide range of concentrations is characterized. The resulting optical fiber sensor can be used for on-line measurements in electrical apparatus that use oil-paper insulation under large electrical field gradients. A light guide such as an optical polymer fiber operating in the 400 nm to 970nm wavelength range is embedded in a body of paper insulation material immersed in oil, with the free ends of the fiber extending to or beyond the edges of the structure so that radiation such as light can be directed through one end of the carrier, and measured at the other end thereof, to monitor and detect the presence of moisture in the interior of the structure. Under normal operating conditions of power transformers the moisture concentration in the oil is in the range of 10 to 100 ppm and 0.5 to 5% in paper for a temperature range of 0 to 100 °C. Oil-insulated power electric equipment such as current transformers in electrical substations can have a designed lifetime of 3 decades, however some equipment in the field has been operated for a period longer than this, therefore questions arise over the reliability of this equipment and in fact, in some occasions, explosions have been reported with the consequent blackout in some region of the affected city, as in [1].

The most common insulation system used on studied instrument transformers is a combination of oil, paper, epoxy resin and porcelain. This kind of insulating materials makes such equipment susceptible to problems like oil leakage, moisture accumulation, paper oxidation and flashover over the polluted creepage. All of these disadvantages contribute significantly to explosion and fires occurrence probability.

There are a number of applications where it would be desirable to measure moisture, but where conductivity measurement is not practical. An example of such application is in the control of moisture in power transformers with paper-oil insulation. Depending on the operating and ambient conditions, the moisture level in the transformer oil can vary significantly. At present, moisture is determined on batch samples taken from the operating transformer, as in [2]. On-line monitoring of moisture in oil would permit control of moisture build but has limitations due to the thermal dependency of equilibrium curves to calculate real moisture in paper, as in [3,4]. On-line monitoring of moisture in the paper used in oil-paper insulation would permit better control of moisture build up within desired limits.

Under normal operating conditions of power transformers the moisture concentration in the oil is in the range of 10 to 100 ppm and 0.5 to 5% in paper for a temperature range of 0 to 100 °C.

Among other advantages, optical fiber sensors have been found to be generally insensitive to electrical interference. Fiber optic chemical sensors have been described using a number of optical phenomena, including absorption across a gap between two fiber ends, fluorescence initiated by light transmitted through an optical fiber and collected by the same fiber, absorbance of light by a substrate at the end of a
fiber with observation of the transmitted or reflected light, tapered optical fiber sensors covered by silica sol have demonstrated good sensitivity, as in [5]. And Bent sensors have been reported based on the use of glass optical fibers covered by silica sol and the effect of evanescent waves at the surface interface of the fiber and water trapped by the silica sol, as in [6].

Of particular interest for the present paper is the technique based on cladding refractive index change to measure humidity at the surface of a fiber, whereby light traveling through the fiber by multiple internal reflections is modulated by the absorption spectrum of the surrounding medium.

II. BENT SENSOR FABRICATION METHOD

The implementation of an optical fiber moisture sensor is based on a polymer optical fiber covered by Polyvinyl Acetate PVA. This technique can be used to produce sensors with different geometries. Some of the sensors where a PVA coating can be applied are: straight fiber, tapered fiber, and bent sensors. In this paper, the implementation of a moisture sensor based on a bent geometry is presented.

To build a sensor, the length or the fiber has to be determined based on the application and the distance to the point where the measurement has to be performed. Once the length has been set, a one centimeter cover has to be removed at the central part of the optical fiber cable. Heat is applied and the fiber is bent 180 degrees such that a horse shoe shape sensor is formed as shown in figure 1.

The process to apply the moisture sensitive PVA layer to the fiber is as follows: One then has to clean the uncovered (one cm long) section of the cable using ethanol to remove oils or grease on the cladding surface. We then proceeded to apply over the cladding a coating layer by layer of the PVA dissolved in ethanol alcohol. The thickness of the layer is obtained by dipping several times as required, in our case we choose three dipping cycles to produce a layer of a proximately 50 micron. A drying time is recommended after each dipping.

In order to have a stable layer the PVA has to be let set for at least 24 hours to guarantee full curing and drying to produce good polymerization.

To test the quality of the PVA deposition, the sensor is introduced in distilled water to see the uniformity of the PVA layer on the fiber. It is easy to observe, by visual inspection, the layer build up. A uniform layer will produce a white color cover layer and should be free of spots or cracks. Once the sensor has been tested for layer uniformity, the sensor is let dry on air.

III. EXPERIMENTAL DETAILS

The evaluation of the optical fiber sensor as presented in this paper is carried out by directly exposing the moisture content to the fiber coating. This procedure was chosen due to the difficulty to establish equilibrium conditions in real oil-paper insulation system in a real electrical apparatus.

We have experimentally studied how the light transmission characteristics of such coated optical fiber change as a function of moisture conditions in oil that are representative of oil-paper insulation. The coating is exposed to different moisture conditions from water saturation to dry conditions and immersed in transformer oil to simulate the conditions under normal operation of electrical power apparatus.

The application of an optical fiber moisture sensor under real conditions requires a pair of sensors, one to be used as reference in contact only with the oil (Sensor in dry condition), and the other to measure moisture in composite paper insulation immersed in oil (moisture concentrations in the range of 0 to 10%).

The characterization of the sensor is performed as shown in figure 2. The measurement set up is comprised of a stable light source, a monochromator with a diffraction grating, a locking amplifier, a light detector an a computer to capture and process the information.
When a light beam is injected into an optical fiber, the light is guided through the fiber by total internal reflection at core-cladding interface.

Porous material PVA is known to scatter light because of the discontinuous structure inside the material. If a polymer material coated on the surface of a polymer optical fiber core with a micro porous structure, affected by the water presence produces a refractive index change, the light penetrating into the coating layer can be scattered out of the coating, as in [6].

The bent probe was tested in a laboratory at 25°C inside of a test tube filled with transformer oil. The probe was subjected to water until saturation and a 100% moisture condition was established and a measurement in air was taken, the water saturated probe was immersed in the transformer oil test tube and a 100% moisture measurement was taken.

The water saturated probe was put to dry on air and inside of moisture capturing container filled with dry silica sol to be able to produce a 0% water reference, and several measurements on air and oil were taken as shown in fig. 3.

A light guide such as an optical polymer fiber operating in the 400 nm to 970 nm wavelength range is embedded in a body of paper insulation material immersed in oil, with the free ends of the fiber extending to or beyond the edges of the structure so that radiation such as light can be directed through one end of the carrier, and measured at the other end thereof, to monitor and detect the presence of moisture in the interior of the structure.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Wavelength response of a PVA-coated bent optical fiber probe exposed to transformer oil at different humidity on the sensor is presented. The calibration curve describing the relationship of transmittance with water content was obtained by using a straight fiber without sensing coating as reference and the results are plotted from 380 to 780 nm in Fig. 4.

The obtained calibration curves shown in Fig. 5 indicate that the sensitivity of measurements performed in air is at least twice that of the measurements performed in transformer oil. A humidity instrument for paper oil insulation can be built from the optical fiber sensor described in this paper and the information obtained from the test described above.

After the measurements were taken, an estimation of the water content under an unknown condition (semi dry) for the sensor immersed in oil has to be determined. Several moisture calculation criteria are applicable such as: area under the curve, one point measurement at a give wavelength and a two points relationship at two wavelengths.

Estimation of the moisture under semi dry conditions considering a linear response for transmittance to moisture is given in Table 1, based on data taken from experiment results shown in fig. 4.

<table>
<thead>
<tr>
<th>Moisture Calculation Criteria</th>
<th>Dry Sensor</th>
<th>Semi Dry Sensor</th>
<th>W Sat. Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA UNDER THE CURVES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLAT REGION (560 nm to 780 nm)</td>
<td>32.2</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>ONE POINT (660 nm)</td>
<td>29.9</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>RELATIONSHIP TWO POINTS MINIMUM (380 nm) TO MAXIMUM (700 nm)</td>
<td>31.7</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSIONS

In conclusion, the evanescent-wave scattering phenomenon has been observed in a PVA coating on the surface of a polymer optical fiber.

This phenomenon was employed, for the first time to our knowledge, to design an optical-fiber humidity sensor using PVA. The advantages of this humidity sensor include: simple structure, low cost, small size, wide dynamic range, and the fact that it is free of interference from electromagnetic fields.

The PVA coating technique has been demonstrated as a suitable method to deposit humidity-sensitive thin films onto the surface. It has also been demonstrated that sensitivity can be tuned by choosing a light source of appropriate wavelength.

Further work is necessary to convert this technique into a practical instrument in power electric equipment. One of the features that can be improved is to use a supply of a known wavelength such as a semiconductor laser or light emitting diode of visible light, instead of a monochromator, and to include a measurement from a reference sensor along with the measurement sensor in the paper. Temperature measurements may be required to improve the accuracy of the measurement, specially to determine low levels of moisture (less than 5%).

REFERENCES