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Simultaneous Measurement of Hot Spot Temperature and Trace Moisture in a High Voltage Operating Transformer Using a Fiber Optics Sensor Pair

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SUMMARY

Moisture and temperature are the two most important factors controlling the life of the transformer. Together, they could accelerate the aging of the mineral oil and the insulating cellulose paper. For every ten degrees C rise in temperature, the expected life of the transformer can be reduced by a half; moisture has a similar acceleration factor. Together, they can rapidly shorten the expected life of the transformer. A standard moisture transport model currently used by the industry assumes that the temperature of the recirculating oil and therefore moisture content within the oil would be uniform throughout the whole transformer. This has been proven incorrect. Some insulation having a hot spot temperature would become the weakest link. These locations would see the earliest failure. The solubility of moisture in oil is temperature and load dependent. If we can measure the trace moisture and temperature directly on the cellulose paper and the pressboard, we might be able to understand the true picture of moisture transport and extent service where aging is taking place. This will allow an accurate model enabling users to predict accurately the residual life and perform trade off in day to day operation while optimizing the transformers life. This challenge is now solved by a fiber optics moisture and temperature sensor based on a special type of fiber Bragg grating called the pi-phase-shifted grating featuring a very narrow filter. The narrow filter allows extra sensitivity of temperature measurement of 0.1 degree and moisture resolution of down to 0.1 ppm. This is a first in the world. Furthermore this type of sensor is immune to high voltages and strong electromagnetic fields that can work in oil with a working life of 25 years. This paper will describe the technology behind the sensor and how these sensors are packaged so that they can be installed during the transformer manufacturing and drying process. We will also discuss a field test with cooperation with a large transformer manufacturer where sensors are wrapped around an actual winding. We will also discuss the process we use to calibrate these sensors to make them a rugged industrial solution.

KEYWORDS

Trace moisture. Hot spots, Transformer Health Index, Phase Shift Gratings

INTRODUCTION

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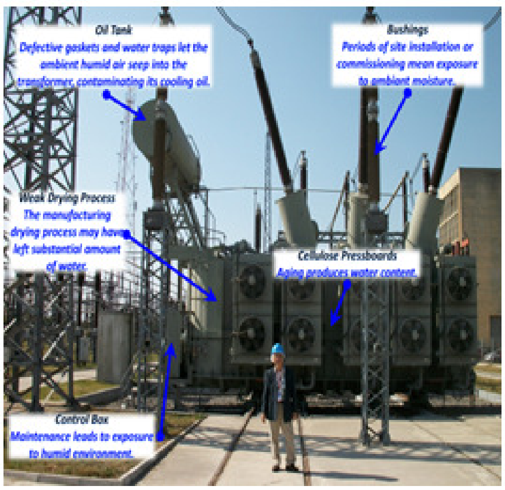
Proper moisture monitoring and management in power transformers avoids premature insulation failure, which is important to prolong the service life. Moisture content rise is ineluctable as it seeps in via leaking tank seals and periods of maintenance. Furthermore, the natural degradation of the organic insulation generates its own water content. Fig. 1 illustrates the concept. Due to the accumulation of moisture, the unfortunate corollary is a snowball effect in the insulation degradation [1].

Two main agents found in a large portion of transformers interact with moisture. On one hand, the oil mostly acts as a transport medium by reason of its low water solubility. On the other hand, the insulating pressboard and paper – made in the majority of cellulose – is omnipresent in the making of internal windings as shown in Fig. 2. Cellulose is some thousand times more prone to be the main reservoir for moisture. Taking into account the effects of increasing temperature and load, the solubility of moisture in oil increases while that of cellulose decreases [2]. Hence, assessing the state of the transformer demands for monitoring migration of moisture under temperature and load influences. A fiber optics based approach – appropriate in a high voltage environment – is illustrated here to diagnose and correlate the aforementioned three key parameters.



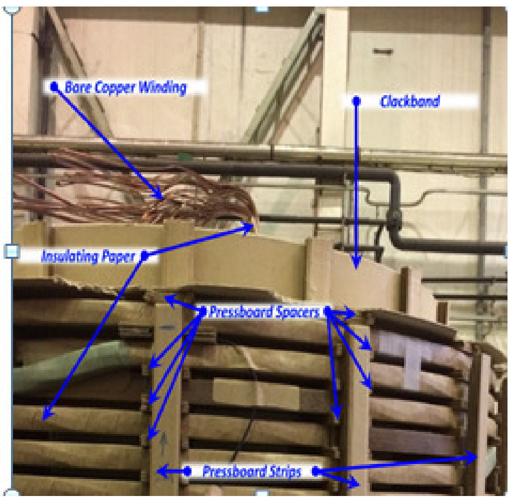
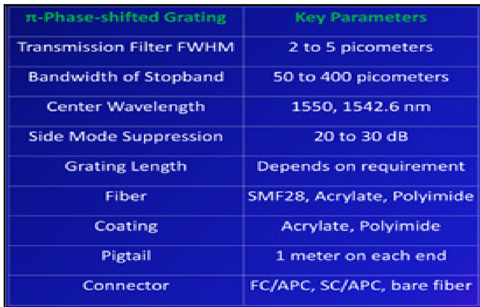


Figure 1:Moisture sources in a power transformer. Figure 2 Lots of organic materail holding moisture

FIBER OPTICS MOISTURE SENSOR WITH TEMPERATURE MEASUREMENT CAPABILITY

The pi-phase-shifted grating (πFBG) provides a very narrow transmission peak. Fig. 3 shows the design specification from which results the typical transmission spectrum of Fig. 4 with a narrow transmission peak of 2 to 5 picometers. This narrow peak needs to be interrogated by a narrow-line DBR laser, enabling us to scan the structure and determine the changes in center wavelength. For temperature measurement it is capable of measuring down to 0.1 degrees C [3,4].



π-Phase-shifted Grating	Key Parameters
Transmission Filter FWHM	2 to 5 picometers
Bandwidth of Stopband	50 to 400 picometers
Center Wavelength	1550, 1542.6 nm
Side Mode Suppression	20 to 30 dB
Grating Length	Depends on requirement
Fiber	SMF28, Acrylate, Polyimide
Coating	Acrylate, Polyimide
Pigtail	1 meter on each end
Connector	FC/APC, SC/APC, bare fiber

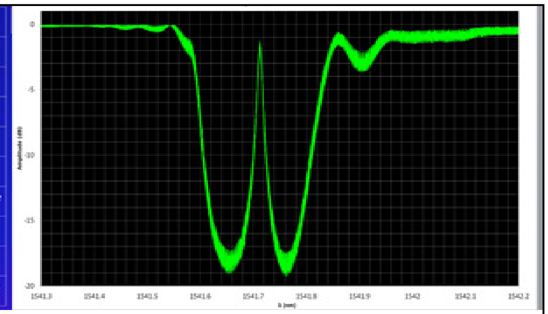
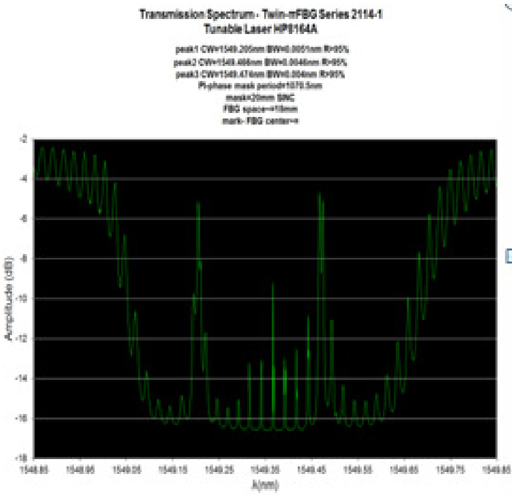


Figure 3: Design specification of the πFBG. Fig 4: It'sTransmission spectrum

The moisture sensor is formed by coating the πFBG area with multiple layers of polyimide, each layer individually cured at 300 degrees C. As the polyimide shrinks, it causes a compressive strain over the grating area, resulting in a downward shift in center wavelength of roughly 400 picometers. Fig.5 is the end result showing a spectrum with two transmission peaks. This pair makes the dual moisture and temperature capability. The lower wavelength peak of said spectrum represents moisture level in ppm, whereas the higher one represents the temperature in its immediate vicinity. Such narrow line width brings very high sensitivity and thus depicts extremely small changes in temperature and trace amounts of moisture. The total length of the pair can be contained within a specially designed package as shown in Fig. 6. The photograph displays a tightly designed vibration sensor of 30 mm in length and 20 mm in width. The combined moisture and temperature sensor is slightly longer but based on the same design principle. The temperature FBG is only 18 mm away from the moisture sensing counterpart. We make sure that the trace moisture measurement is relevant (moisture solubility in oil is temperature dependent). The sensor pair is housed in special high temperature packaging material (PEEK) which is mechanically strong and can stand up to 300 degrees C. The selection of this specific material is to facilitate the transformer drying process. During transformer construction OEMs subject the assembled windings with the embedded sensors to a 150 degrees C vacuum bake for 5 to 6 days. This package protects the sensor from damage due to this high temperature prolonged exposure. The moisture and temperature sensor pair package roughly measures 50 mm as a whole. The package can be fitted into a matching slot cut out on the pressboard spacer separating two neighboring windings, thus providing further mechanical protection. In fact, this spacer is part of the original transformer design. Locating the sensor strategically in the spacer, direct measurement of moisture inside the flowing mineral oil becomes feasible. To measure the moisture immediately on the surface of the cellulose paper, the molded sensor will be wrapped underneath it.



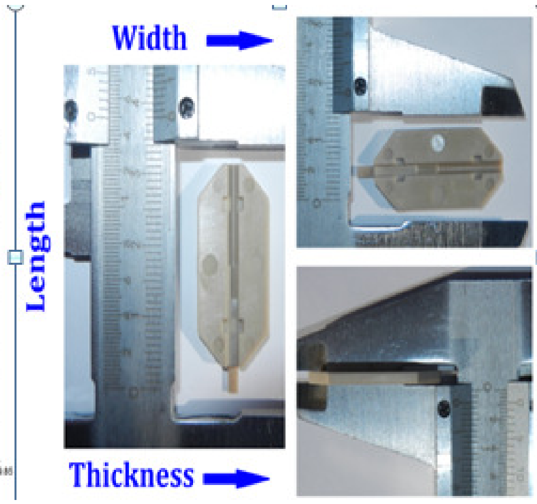
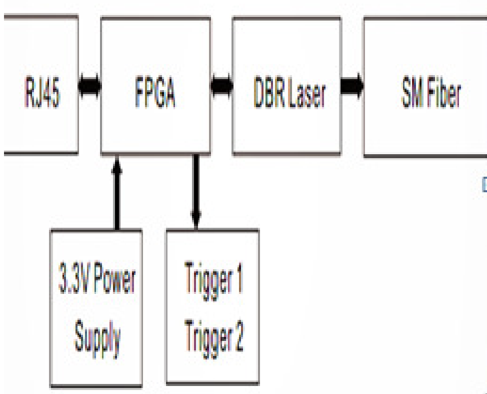
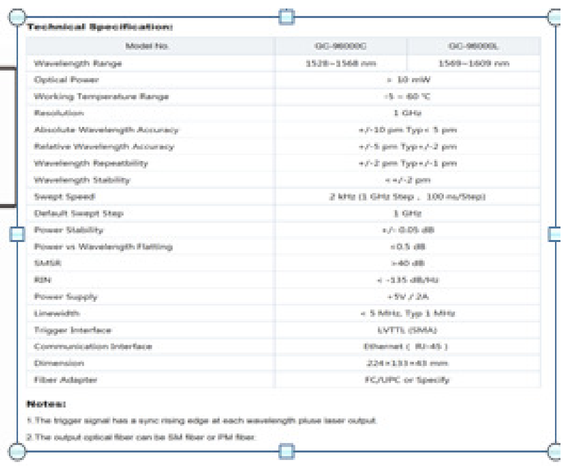


Fig.5: The Moisture/temperature sensor Spectrum Fig 6: The improved open frame pacakge

TUNABLE LASER FOR INTERROGATING AN ARRAY OF MOISTURE SENSORS

The interrogation system is based on a fast swept tunable laser with a typical line width of 1 MHz and can be interrogated at a resolution of 0.1 GHz or 1 pm steps. Designed with a DBR structure with four independent current sources, driving a fast index adjustment function, (see detailed specification of Fig. 7), it is specially designed to interrogate the moisture/temperature sensor based on the very narrow transmission filter found in the πFBG. The laser has an Ethernet interface and a high speed FPGA as shown in Fig. 8. The electronic control can sweep at 1GHz step, which is faster than other interrogation systems built to support standard FBGs. As a result, it covers the full C band of 4400 steps all within 1.5 seconds. The laser can support spatial multiplexing of up to 16 sensors with 20mW of optical power. Alternatively, moisture/temperature sensor pair can be implemented in an array. The system can support 16 arrays.





Technical Specification:

Model No.	GC-96000C	GC-96000L
Wavelength Range	1528~1568 nm	1569~1609 nm
Optical Power	> 10 mW	
Working Temperature Range	-5 ~ 60 °C	
Resolution	1 GHz	
Absolute Wavelength Accuracy	+/-10 pm Typ< 5 pm	
Relative Wavelength Accuracy	+/-5 pm Typ+/-2 pm	
Wavelength Repeatability	+/-2 pm Typ+/-1 pm	
Wavelength Stability	< +/-2 pm	
Swept Speed	2 kHz (1 GHz Step , 100 ns/Step)	
Default Swept Step	1 GHz	
Power Stability	+/- 0.05 dB	
Power vs Wavelength Flatting	<0.5 dB	
SMSR	>40 dB	
RIN	< -135 dB/Hz	
Power Supply	+5V / 2A	
Linewidth	< 5 MHz, Typ 1 MHz	
Trigger Interface	LVTTL (SMA)	
Communication Interface	Ethernet (RJ-45)	
Dimension	224×133×43 mm	
Fiber Adapter	FC/UPC or Specify	

Notes:

1. The trigger signal has a sync rising edge at each wavelength pluse laser output.
2. The output optical fiber can be SM fiber or PM fiber.

Figure 7: Tunable laser with Ethernet interface **Figure 8:** Beyond the ITU Grid covering either C-band or L-band.

WORKING INSIDE AN OPERATING TRANSFORMER AND FAILURE ANALYSIS OF OUR FIELD TEST

In a high voltage transformer, any air bubbles can lead to arcing, especially air bubbles containing moisture. Air bubbles can be trapped in a fiber optics cable jacket and inside the sensor package, which ooze into the oil. These air bubbles inside the oil can also form on the surface of the cellulose paper and become locations where partial discharges occur and damage the insulation. In addition, as part of the manufacturing process, assembled windings sets would be subjected to a 150 degrees C vacuum bake with the reducing atmosphere impregnated with kerosene vapor for 5 days. The kerosene vapor acts as a heat transfer agent causing water to vaporize and become easier to remove. Ordinary Telecom fiber is coated with acrylate and can stand only up to 80 degrees C. In the meantime, the acrylate could also be attacked by the kerosene vapor. The patch cord jacket contains aramid trapped full of air as a buffer. We used a 900 µm Teflon tube, but there is still air inside the tube. The first field test included drying the windings with the sensor installed in the OEM standard drying process. After drying, many sensors became non functional. Subsequent failure analysis revealed weakness in the heat shrink used to couple the thin fiber onto the Teflon tubes. They became distorted producing micro-bends on the fiber. Meanwhile, the connector seems to have survived. We found that their connectivity was not affected. Fig. 9 shows such example of said components. The sensor package material that was initially 3D printed is supposedly rated to stand up to 100 degrees C. It became discolored and its cavity collapsed during the vacuum drying. The package actually touched the fiber inside. Fig. 9 shows how the fiber position before the drying. Fig. 10 illustrates the collapsed package after the drying process. Fig. 11 showed the failed devices with all the damages.

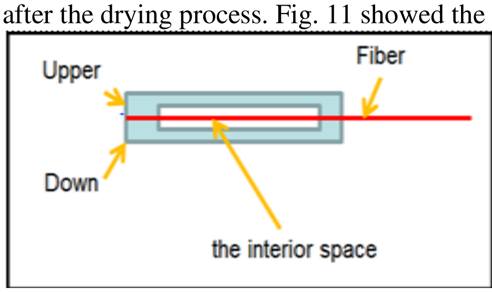


Fig 9: Before vacuum bake

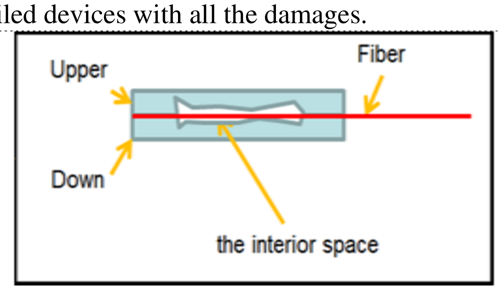
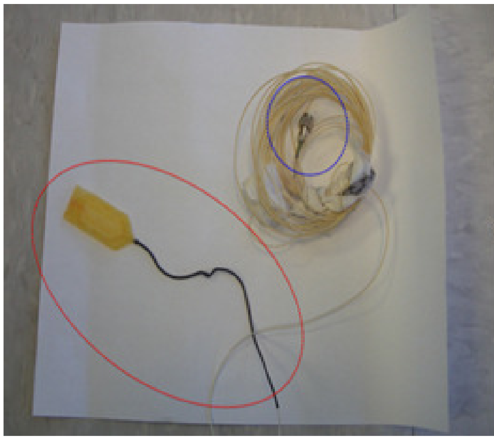


Fig 10: After high temperature/vaccum, the top lid collapsed

The next section will discuss our new design. It became an open package instead of a top and bottom lid. In the new design air is simply removed. Fig. 12 shows the key design differences. We also found that the fiber had been detached, the high temperature epoxy we used could not stand up to the drying process. Our first field test inside the transformer resulted in sensor failures. Subsequent failure analysis showed that the fiber had been detached and the heat shrink tube used to hold the fiber became completely destroyed. Apparently, the high temperature epoxy that we used does not work well at 150 degrees C. Learning from this experience, we have found an epoxy better suited to handle prolonged exposure. We were not expecting the drying process of the OEM, we thought under normal operation a transformer would run at 90 degrees C. It is important to find out what drying process is used by the OEM. In the new design the sensor package is designed with an open frame so that the air can be sucked out during the same drying.



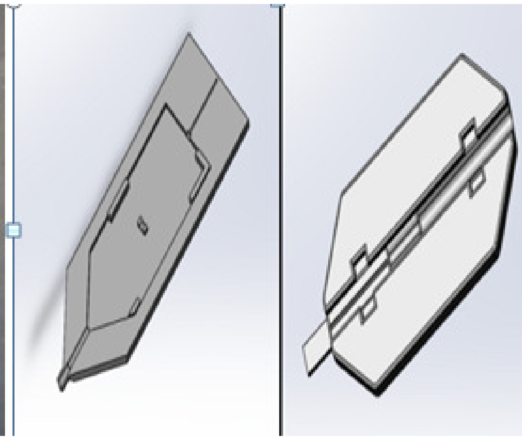


Fig 11: Failed sensors showing all damages Fig 12: Details of the open frame package

The patch cord that links from the sensor head to the hermetic junction plate will use polyimide coated fiber which can work up to 300 degrees C. Better mechanical support is provided to the fiber. A PEEK material spiral is used for the cable jacket and is essentially porous. In the previous field test, we used Teflon tube. Teflon is able to stand the high temperature but is too soft and does not provide enough mechanical protection.

The drying process used by the OEM becomes the toughest challenge. Besides the rigorous vaccum bake , the industry is interested insulation material that can operate at higher temperature. As a result , we opted to design in a material that can stand up to 300 degrees C. This over design will future prove our sensors. Besides our sensor, we have also implemented similar high temperature material for our optical cabes, jackets, connectors. Test has been performed to assure that mineral oil and Ester would not introduce higher insertion loss. We are guided by the same principle that qualified our process under the Telcordia program, enableing our sensor to work for more than 25 years.

Reliability testing and calibration

It is important to perform rigorous reliability tests before we perform another field test. The open frame design, along with 900 µm PEEK tube (stiffer than the Teflon tube) and PEEK spiral wrap make the cabling system air-free. We have established a set of rigorous reliability tests with the help of Professor Hua Lu of the Ryerson University. Another important problem remains to be solved. The moisture/temperature sensor is designed to measure trace moisture. Moisture exists in our production area, it is important to prebake our sensor and have them vacuum packed with desiccant. We notice that when we produce the moisture sensor, the separation between the two peaks has reduced from the expected 400 pm. Obviously, the sensor must have absorbed some moisture from the room. We are seeking co-operation with Celestica, our industrial partner to guide us in our sensor packaging method. Beyond this problem we will have to perform calibration. This will be performed by Centre National en Electrochimie et en Technologies Environnementales (CNETE).Calibration will be performed with a tunable laser based interrogation system mentioned in section 3. In our calibration, the insulation fluid is the mineral oil used inside transformer and heated at different temperatures. The small concentrations of water is measured by a coulometric titration method. This technique is based on the reaction of iodine with water in the presence of SO2. Molecular iodine is generated in solution by electrochemistry and reacts with small concentrations of water of the order of magnitude of ppm (p/v). The end of the titration is detected by platinum indicator electrodes. The system permits discrimination of concentrations of the order of magnitude of 0.1 ppm. In the actual setup, the system was put in contact with an oil matrix with water content of 2 ppm to 40 ppm of water. The precision of the detection system of QPS Photronics will be evaluated in this concentration range. A calibration graph will be generated to evaluate the relationship of the system signal and the moisture concentration. Another reference is planned for Ester which has higher moisture solubility.

Conclusion

We hve developed a fiber optics moisture /temperature sensor that can measure the moisture Transport up close inside the transformer and these will be useful in OEMS and companies in the supply chain to better validate their new materail and transformer design. To make transformer safer OEMs want to switch to Ester: Ester has a higher ignition temperature and would reduces the risk of an explosion when failure occurs. There is also the search for insulation material that can run at higher temperature; such as Aramid paper versus Kraft paper. The ability to run the Transformer at higher temperature means OEMs can reduce its size and weight and therefore cost. After consulation with our OEM partners, we have decided to establish various sets of moisture references spanning from the low end of 2 to 20 ppm. Another reference for Ester with its measuring range will be determined once we perform more research. Forward thinking OEMs realize that trasmission voltages will continue to rise, such as the Ultra high votage network of 1100 KV. Such high votlage would demand OEMs to further remove mositure as part of their manufacturing process. Hence there will be a need to measure extremely small amount of moisture. After all the lessons we have learned from our last field test in China, while having made all the improvements mentioned in this paper ; we plan to perform another field test in Q1 2018. This field test will be performed with Northern Transformer , located in Toronto, Canada. The OEM will also work with us to experiment on moisture measurement in Ester. We are prepared to fabrcate sets of calibration standards : one for mineral oil and another set for Ester. We will measure the higher solubility of mositure in Ester and report its impact during overload.
Based the possible choice of mineal oil and ester ; we are happy that our partner CNETE , is equipped with a full suite of professional spectroscopic equipments. We plan to place our pretested (golden standard) sensor into sealed containers of different fluid. Calibrartion will involve both our sensors and system interrogation unit to be shipped. The next field test wiil involve all our fiber optics sensors : moisture/ temperature, vibration, and PD sensors.

ACKNOWLEDGMENTS

We are grateful to be co-operating on the development of the fiber optics moisture/temperature sensor with the following partners: Professor Xijia Gu of Ryerson University on the πFBG, Professor Hua Lu, also of Ryerson University who both performed the reliability tests. Acknowledgements also go to Professor Mojtaba Kahrizi and Professor Bowei Zhang of Concordia University. A second field test is being arranged with Northern Transformer in Toronto. Special acknowledgement goes to Celestica who will help us design the sensor packing methods.

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