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Assessing Water Content and Vibration from Dynamic Measurement in Transformer.

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SUMMARY

A thin fibre optics sensor has been developed to fit into the winding spacers, without any disturbance to the cooling oil flow, for measuring the winding vibration, temperature and moisture. The innovation is aimed to help the transformer users to safely extend service lives of their assets and to mitigate risk of unscheduled shutdown due to premature equipment failure. The proposed sensor, which is 2 mm thick, 30 mm long, and 14 mm wide, can measure vibration between 2 Hz to 2 kHz. A self-calibration algorithm is introduced to compensate temperature variations, which delivers an indirect method to measure temperature. The sensor is calibrated for moisture ppm measurement of Ester and Mineral oil. The calibration curves show consistent results and the relationship is quite linear in the low ppm region. The optic fibre based sensor is installed inside the transformer and the resulted measurements are no longer affected by various noise sources from peripheral equipment. The obtained results indicates that the sensor has high potential for on-line monitoring of transformers. Using the improved sensor will provide solutions to transformers integrity in smart grids, assuring the system reliability. The knowledge and technology that will develop from the proposed research are of great importance to both Canadian manufacturing and power utility industries.

KEYWORDS Condition monitoring, power transformers, moisture content, vibration, temperature.

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1. Introduction

Power transformers are important and one of the costliest equipment used in the transmission and distribution of the electric energy[1]. Despite great progresses in their design in recent years, the Achilles heel still remains the insulation system. When power transformers fail, the fault can be traced usually to defective insulation [2, 3]. Unexpected failures cause major disturbances to operating systems, resulting in unscheduled outages and power delivery problems. Extreme reliability is demanded of electric power distribution as when failures occur they inevitably lead to high repair costs, long downtime and possible personal safety risks [1]. By accurately monitoring the condition of the insulation (moisture ingress, temperature, vibration, etc.) many types of faults can be discovered before they become serious failures and outages.

In power transformers, oil impregnated cellulose-based paper is the main insulating material of the system. Oils are used alone as electrical insulation only in areas of a transformer where, by design, voltage stresses are relatively low. Whereas solid insulating materials are used in transformer areas where voltage stresses are high, or where a particular physical configuration is needed. The ready supply of cellulose and mineral oil has, therefore, made these the materials of choice for nearly a century [4]. Transformer life/aging is mainly related to the degradation of the insulation system [3]. Actually, the "end-of-life" of transformer ="End-of-life" of cellulose-based paper isolation [2]. The Achilles heel of cellulose is the fact that it is vulnerable to water content (considered as enemy number one of transformers is comparable to cholesterol in our blood), vibration, oxygen, and to excessive heat [5]. Because water content in oil varies with temperature, moisture measured by sampling of the oil does not give a clear picture. Online monitoring by optical sensors is the key for sensing the real condition of the unit. Since water content must be related to saturation characteristics, which vary with chemical composition of oil and service-aging condition, the determination using relative saturation is therefore more convenient.

The general trend towards the so-called "smart" digital systems and the continued reduction in the cost of these technologies, combined with the existence of a communication infrastructure in a growing number of facilities, have facilitated the implementation of monitoring technologies. QPS has been active developing fibre optic sensors for the power industry helping plant owners monitor moisture, vibration and temperature inside generators and transformers[6]. Some of the research and development accomplishments by QPS Photronics during the past years have resulted in the development of a Phase Shifted Gratings recoated sensor with multilayered of polyimide films. This fibre optic sensor is designed to help plant owners monitor moisture, vibration and temperature inside oil-filled transformers. This contribution aims at analyzing test data records based on laboratory tests. While moisture ingress and excessive heat can lead to catastrophic failures, vibrations can induce Turn-to-Turn Fault (TTF) [2, 7]. The TTFs in transformer winding are caused by insulation aging, deterioration by thermal over-loading, high transient voltage stresses, mechanical vibrations, and external short circuits [8]. TTF is one of the most common faults in transformer that cause catastrophic events such as transformer explosion, winding, or core deformation [9].

Moisture, which is coming from the residual after initial factory dry-out, ingress from the atmosphere, aging decomposition of cellulose paper, and aging decomposition of oil, causes rapid aging of the insulation and its eventual failure. As a practical matter, moisture accumulates in all transformer designs over the years. While a small portion is found in the oil, some 98 to 99 percent of it becomes diffused in the tons of paper (cellulose) insulation. Without moisture maintenance, every power transformer over 15 to 25 years of age can be expected to be "wet," that is containing 2.5 to 5 percent of moisture by paper weight, or more. The potential for serious damage to the transformer at these levels of moisture is well known.

As a result, having a real time diagnostic solution capable of predicting moisture-related hazard danger in advance would increase the operability time of transformers.

Having invented the phase mask method of writing in fibre gratings which enables volume production at low cost by exposing multiple fibers simultaneously, QPS Photronics is a pioneer in the field of fibre optic sensors based on the fibre Bragg grating (FBG) technology which is forming the interference cavity for vibration, temperature and moisture sensing.

In this paper, the detection mechanism developed to use of the FBG fibre optic sensor to measure temperature, vibration and moisture is discussed. Fibre Optic Sensors are made with glass and can work inside a transformer; they have a long life and immune to the high voltage and the electromagnetic field providing real-time monitoring solutions. Optical switch technology would allow us to customize any sensors and system configuration.

The paper is structured as follows: Section 2 introduces the design and detection method for the fibre optic vibration/temperature sensors. Section 3 presents the design considerations of moisture sensor with temperature compensation and the way the information provided by these sensors can be processed. Temperature measurement result will be given in section 4. Finally, section 5 summarizes and concludes the discussion.

2. Long Gauge Vibration/Temperature Sensor

The ability to measure both vibration and temperature is based on the FBG interference cavity: two identical gratings are printed on the same fibre at a small distance, which forms a cavity. When a laser beam with matching centre wavelength is launched into the cavity, it gets reflected and goes through a 180-degree phase shift, giving rise to two interfering beams and dense spectrum of fringes as shown in Fig.1.

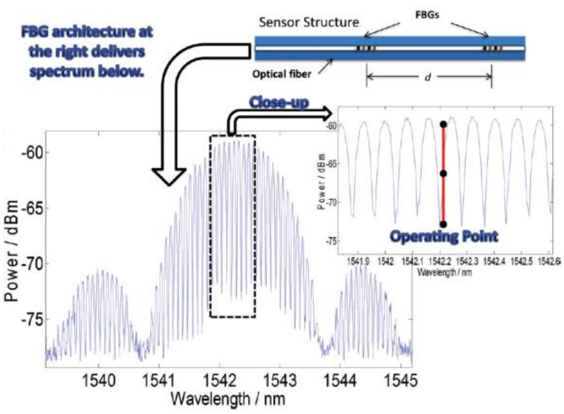


Fig.1. VibroFibre sensor structure.

The larger the cavity length, the denser will be the fringe pack with stepper slope, playing on sensing sensitivity. The vibration function is realized by programming an operating point at the midpoint of the rising slope of a selected fringe.

The interrogator emits a narrowband laser signal whose central frequency is phase-locked to the one of the reflection spectrum of the VibroFibre. The operating point stays locked using both the laser current (LC) and the thermoelectric cooler (TEC) analogue controls of the laser. Environmental effects such as vibration will cause the sensor spectrum to shift right and left, it forces the operating point to ride up and down the slope, translated into intensity changes, which is observed in terms of voltages via embedded photoelectric transducers. With electric changes of now and then compared, vibration data can be displayed as well as the embedded laser signal keeps tracking the sensor spectrum for maximal sensitivity. Since the cavity is also affected by temperature, a self-calibration algorithm is introduced to re-stablish the operating point and such compensation delivers an indirect method to measure temperature. Fig. 2 illustrates how electrical voltages seen from the photo-electric transducers would shift from a low to a high point periodically as the sensor spectrum moves back and forth.

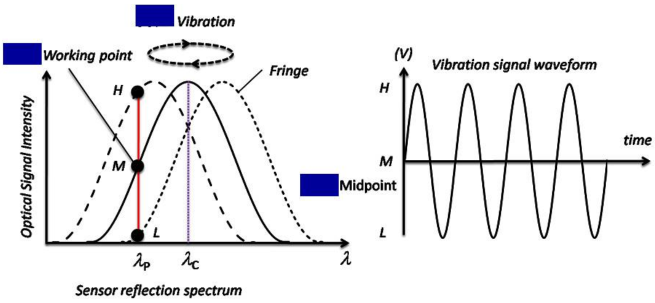


Fig. 2. VibroFibre signal response based on the linear slope of tallest interference fringe.

Our original VibroFibre – developed to monitor vibration at the end windings in large power generators – mainly captured vibration signature via the sensor head (discrete sensor). With *sine qua non* sensor modifications and a signal enabler coming from the interrogator (signal conditioner unit), the long gauge VibroFibre was born as a distributed sensor. The original VibroFibre design had a diving board to enhance its sensitivity. However, the resulting thickness (8 mm) made it unfit to the narrow gap between coil turns of transformers. Fortunately, it was discovered that by splicing a length of single mode optical fibre into the cavity, the whole fibre became a distributed vibration sensor. The innovation has turned the vibration sensor into a wideband one since the fibre is now resting freely inside a 900 µm Teflon tube. The proposed new sensor is 2 mm thick, 30 mm long, and 14 mm wide in size (Fig. 3(a)). Fig. 3(b) illustrates how a slot is cut into the press wood spacer to fit the thin sensor. The spacer acts like a package and protects the sensing fibre without obstructing the flow of the cooling oil.

(a) (b)

Fig.3. (a) An open-faced, 3D printed sensor package allows trapped air removal and temperature measurement, (b) Long Gauge VibroFibre thin head set into a press wood spacer.

Fig. 4 illustrates how the thin sensor fits inside a spacer installed between two adjacent windings. The sensor measures wideband vibration signal from 2 Hz to 2 kHz. The translated mechanical vibration to an electrical signal, inside the interrogation unit in the control room, allows signature analysis that detects windings buckling, distortion, and structural looseness. The sensor has been constructed with material that can survive the extended 150 degrees C vacuum bake by OEMs to minimize the moisture inside the paper, no trapped air inside the package and connection cables.

This sensor is currently in production and a laboratory test is being prepared with a scaled down transformer. A field test is also planned. This will be the first demonstration to show the technology's unique capability in observing various vibration signatures in relation to the winding looseness, movement and distortion, etc. However, the preliminary results indicate that the time domain vibration pattern of new transformers give clean sine waves, while the signal from the same transformers that had been used for an extended period, showing slightly disturbed signal due to structural looseness. When the signals look very busy with many frequency components, it is suspected that the windings might have been highly distorted due to some mechanical faults like as buckling [9,10]. Detailed report will be provided soon in the authors' future contribution.

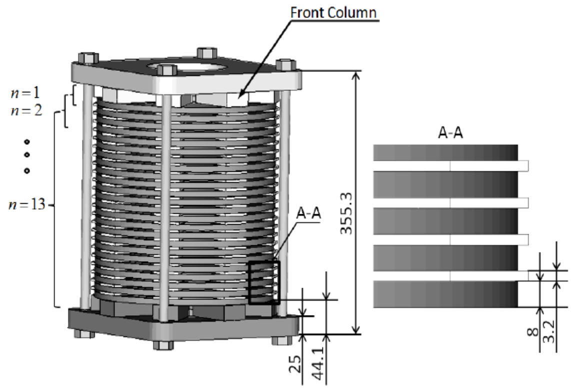
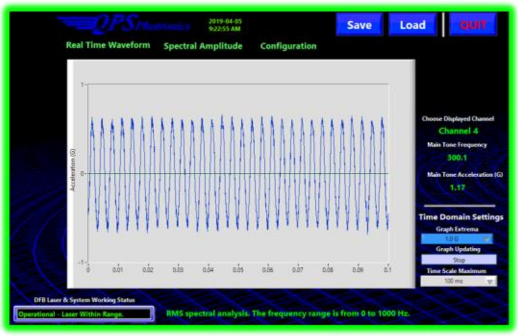
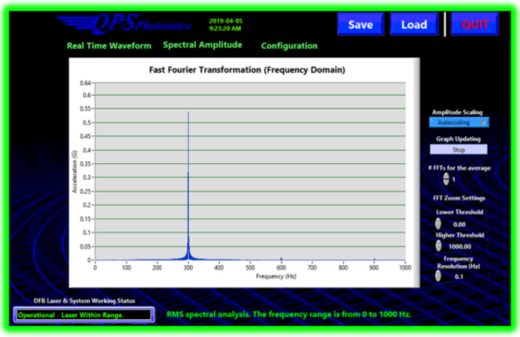


Fig 4. The thin sensor fits inside a spacer installed between two adjacent windings.

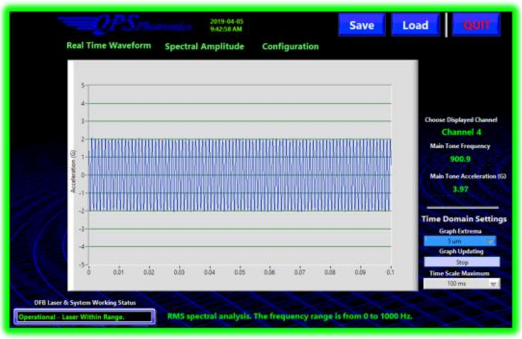
To calibrate the sensor for vibration measurement, it is subjected to vibration stimuli from 20 Hz to 1 kHz by a shaker. Transformers usually emit vibration signatures ranging from DC to 1 kHz, so this frequency rang will be sufficient for assessment of the sensors and vibration survey. Fig. 5 depict the frequency and time domain vibration signal captured by the sensor at 300 Hz & 900 Hz respectively. As it is obvious from the figures there is a good vibration response and the sensor can easily track the applied vibration signal.



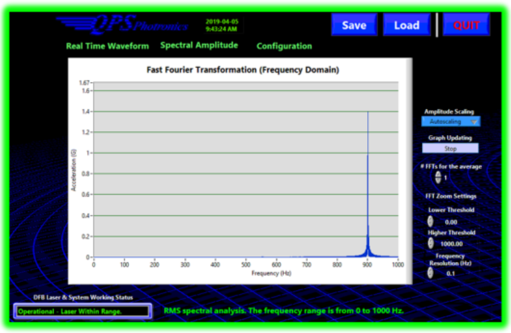
(a)



(b)



(c)



(d)

Fig 6. (a)- (b): Frequency and time domain vibration signal captured by the sensor at 300 Hz, (c)- (d): Frequency and time domain vibration signal captured by the sensor at 900 Hz.

3. Moisture Sensor with Temperature Compensation

The moisture sensor is an extension of our vibration sensor structure. The concise cavity length gives rise to a very sharp peak for accurate ppm measurement. Coating this phase shift gratings generate the moisture sensing function with ten layers of polyimide. With ten layers of polyimide on the phase shift gratings, during curing, the material will shrink and compress the fibre, causing a lowering of its centre wavelength. Another identical phase shift gratings will be designed on the same fibre but with ordinary acrylate coating. This phase shift gratings with conventional coating become the temperature reference. The two peaks corresponding to ppm moisture (lower peak) and temperature (higher peak) are demonstrated in Fig. 6.

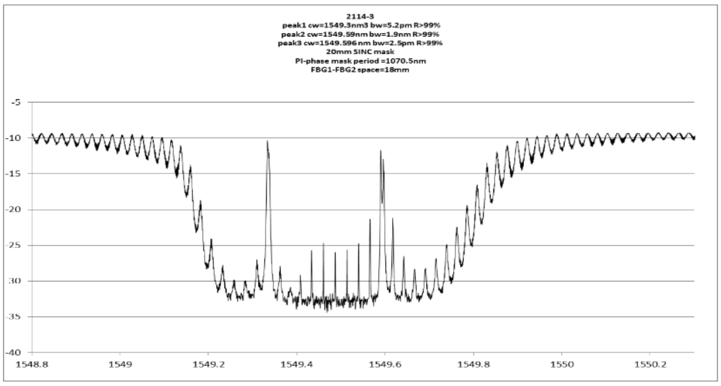


Fig. 6. The lower peak measures ppm moisture, the higher peak measures temperature only.

The presence of moisture would release the strain on the polyimide and the two peaks would move closer together. The distance between the two peaks thus can be calibrated to ppm of Moisture measured. The temperature reference peak which helps to remove the influence of temperature, is necessary because moisture solubility in oil is temperature dependent, placed jointly like this forms the built-in temperature compensation.

The moisture sensor structure and how it is connected to the main frame interrogation unit have been represented in Fig. 7. The sensor has a pair of phase shift gratings measuring a total of 60 mm. Fig. 8 shows the interrogation unit used in the calibration, and it is also the main frame for our entire fibre optic sensor

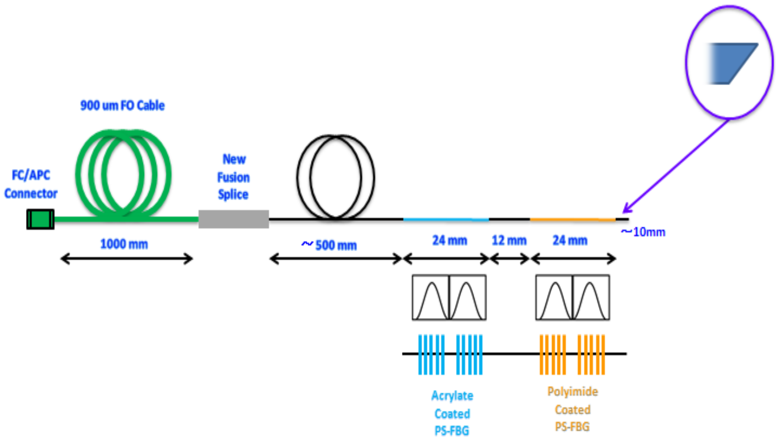


Fig. 7. The ppm moisture sensor and its connection to the central frame unit.

A. Power plug
B. Fiber optics input (FC/APC).
C. Laser control USB connector.
D. 16-bit Datalogging USB connector. Datalogger USB-6210 at right.
E. Power switch.
F. Photodiode output (V) and two laser control (V) analog signals.
G. Twisted pair cable for DAQ by USB-6210.

Fig. 8. QPS Transformer guard used to collect the calibration data.

For the calibration of the sensor, long hermetically sealed glass tubes, as shown in Fig. 9, were used to hold the insulation fluid under test together with some desiccant. The sensors were introduced into the tube using a surgical needle through a self-sealing membrane to prevent moisture from contaminating the fluid.

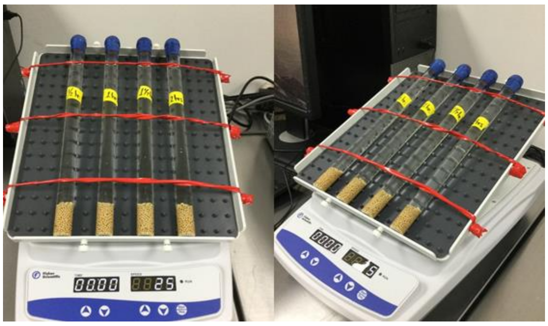


Fig. 9. Hermetically sealed long glass tubes used to hold the insulation fluid under test.

The calibration curves for MIDEL 7131 (Ester) and mineral oil are reported in Figs. 10 and 11 respectively. Fig 10 Shows the calibration curves of MIDEL 7131 (a synthetic Ester-based fluid) where it can be noticed that all three runs show consistent results and the relationship is quite linear in the low ppm region. The maximum moisture was found to be 340 ppm at room temperature of 22 degrees C.

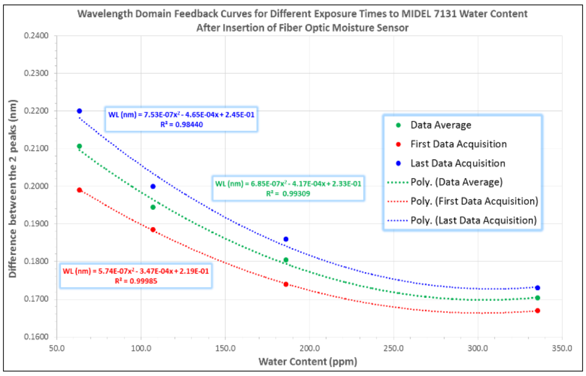


Fig 10 Calibration Curve of MIDEL 7131.

Fig. 11. Shows the calibration curve of the mineral oil, used in most of the existing transformers. The much lower moisture solubility of the conventional mineral oil can be depicted here where the maximum ppm was found to be only 32 ppm at the same room temperature of 22 degrees C.

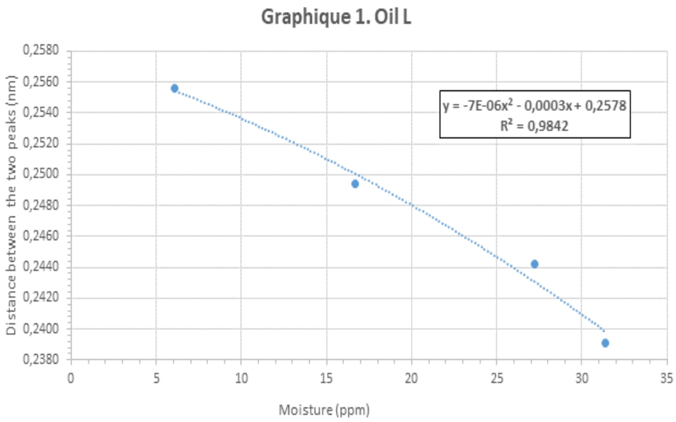


Fig 11. Calibration curve for mineral oil

4. Temperature Measurement

Following temperature calibration, a temperature measurement was performed. Fig. 12 illustrates temperature survey from 30-70 °C of QPS sensor along with interrogation system while comparing with an ideal imaginary probe. The green data points are experimental values from which the blue linear regression arises. The coefficient of determination (R2) informs us how tightly packed these data points are around the linear regression. As for the yellow dash line, it represents an imaginary perfect probe that cannot be found in the real world; measured values are exact. Alternatively, it would mean the oven displays perfect temperatures and same goes for QPS sensor.

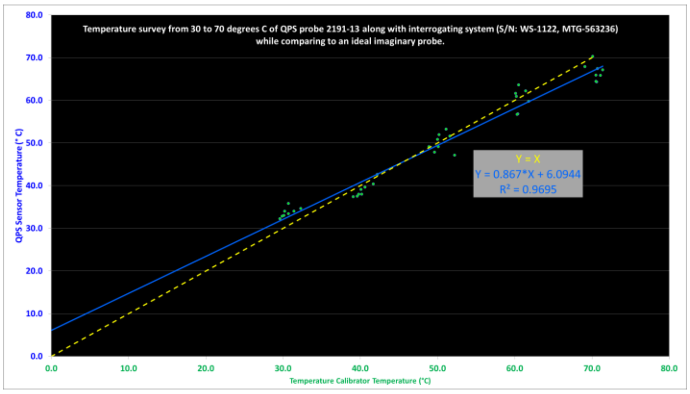


Fig. 12 illustrates temperature survey from 30-70 °C of QPS sensor along with interrogation system while comparing with an ideal imaginary probe.

5. Conclusion

The paper presented and discussed a technical diagnostic solution to tackle the most critical problems that arise in power transformers and may shorten the operability life span of the transformer. A fibre optic vibration sensor is proposed to simultaneously measure vibration and fast temperature change, which can be extended to absolute temperature monitoring. Based on the same measurement principle, a new sensor was proposed to measure moisture content, which, combined with temperature measurements, can be correlated to moisture change in oil. Ongoing research and development also include developing a fibre optics based partial discharge sensor, which will be presented at the authors' future contributions.

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