ASIA TURBOMACHINERY & PUMP SYMPOSIUM
12-15 MARCH 2018
SUNTEC SINGAPORE

NOVEL FIBER OPTIC TECHNOLOGY MONITORS IN-SLOT VIBRATION AND HOT SPOTS IN AN AIR-COOLED GAS GENERATOR

Peter Kung
President
QPS Photronics, Inc.
Pointe-Claire, Quebec, Canada
Peter@qpscom.com

George F. Dailey
Senior Consultant
QPS Photronics, Inc.
Pointe-Claire, Quebec, Canada

Dr. LuFan Zou
Product Manager
OZ Optics, Ltd.
Ottawa, Ontario, Canada

Craig Spencer
Director Asset Management
Calpine Corporation
Houston, Texas, USA

Robert Idsinga
Director of Marketing
QPS Photronics, Inc.
LaSalle, Quebec, Canada

Peter Kung is the president of QPS Photronics, Inc. The company specializes in fiber optic online condition monitoring solutions using advanced fiber Bragg grating (FBG) technology serving the power industry for monitoring generators and transformers. Mr. Kung has solved difficult monitoring problems through innovation and collaborates internationally via a network of partners. For transformers, a separate product line is being developed focusing on simplicity: ease of installation and readily accessible data via the internet of things (IOT) functionality supporting diagnostics and residual life modeling.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to Calpine Corporation for allowing and facilitating the installation of the fiber optic sensing systems at the Hermiston Power Project plant. Likewise, contribution from Oz Optics, Ltd. is highlighted for providing temperature records from their Brillouin distributed temperature technology. At last, acknowledgement is given to the senior consultant George F. Dailey for bringing all participants together for this successful field test.

ABSTRACT

Gas-fired and air-cooled generators are becoming very popular as replacements for climate changing coal-fired generators where they are used in conjunction with solar and wind generators to balance the grid. However, they are subjected to continuous start-stop-load cycles related to thermal/mechanical stresses, and continuous vibration as well. Furthermore, the machines are designed to run at highly efficient material use and close to its design limit. One emerging issue is the occurrence of hot spots in the stator core where thousands of insulated carbon steel laminates are tightly pressed and clamped together. Damaged insulation can cause large Eddy currents to flow leading to core damage or machine shut down.

Another important problem is vibration sparking: excessive vibration loosens the structure. When the amplitude becomes excessive, the carbon paint that makes ground contact with the stator becomes momentarily disconnected. High voltage will build up at random defect sites, causing arcing to take place and resulting in a corona discharge. When this plasma generated by said discharge becomes interrupted by the same excessive vibration, it will begin to electro-etch, eroding the conductive paint and the mica insulation underneath. This paper will describe a new online distributed vibration monitoring technology which consists of a simple length of single-mode fiber connected to a cavity (two identical FBGs forming a Fabry-Perot cavity). At the same time, a Brillouin technology based distributed temperature sensor which measures hot spots is installed simultaneously. It will also discuss a field test jointly conducted with Calpine Corporation and will report the results observed. The paper will explain how the technology functions. Besides the distributed vibration sensors, two fiber optic vibration sensors were mounted on the neutral lead and bus structure of the phase C conductor. These sensors were wideband: they can measure vibration frequency from 10 Hz to 1 kHz.

INTRODUCTION

Hot spot measurement was performed in a random wound electric machine coil. The measurement was found to be affected by the vibration of the rotating machine, resulting in an increased tolerance proportional to the RPM of the motor (Mohammed and Djurović, 2017). An alternative method was actually developed earlier allowing simultaneous measurement of vibration and temperature to monitor the end winding of a large power generator (VibroSystM, 2010). Unfortunately the sensor was packaged in a diving board structure inside a hermetic sealed package with trapped air which became slow in response to changes in temperature. Other fiber optic sensors were developed but could not measure temperature and are too bulky to fit inside the slot (Tetreault, 2008). Eventually a thin vibration sensor was developed for monitoring winding vibration inside the transformer (Kung, et al., 2016) making use of the long gauge effect: namely a length of single mode fiber spliced onto the cavity rendered the whole fiber a distributed vibration sensor.

THE FIELD TEST

This field test was performed in cooperation with Calpine Corporation. An earlier borescope inspection at their Hermiston, Oregon plant revealed that the windings inside their gas-fired generator were showing signs of disturbance. The company ordered a rewind: the project involved pulling out the rotor and therefore became an opportunity to investigate what fiber optic sensor can do to provide more online real-time information how the degradation took place. To measure hot spots, Oz Optics, Ltd. joined to install their sensing fiber optic device. They provided a solution tapping on Brillouin effect, featuring a long sensing fiber optic loop. Given the uncertainty of the top temperature within this particular generator, working reliability is ensured by opting to use the standard single-mode fiber (SMF28) coated with polyimide. It enables the sensing fiber to stand up to 300 degrees C. Normal SMF28 coated with acrylate would only run at 100 degrees C. To further protect the sensing fiber, a long length of Teflon tube houses it, spliced on two FC/APC connectors. It forms a continuous temperature measurement sensor. As for vibration measurement, two types of sensors were used. Both sensors are based on the long gauge distributed sensor technology. One sensor was placed inside the slot; the vibration measuring fiber was made to be five meters, the full length of the gas generator.

The two other installed vibration sensors had their design derived from the transformer application. The actual vibration sensing fiber length was only 15 mm. Standard wideband performance (10 Hz to 1 kHz) defined by transformers is equally valid for generators. The neutral end winding lead and bus received each their own fiber optic sensors.

THE PROBLEM: HOW HOT SPOTS WORK TOGETHER WITH VIBRATION SPARKING TO DESTROY YOUR GENERATOR

When Calpine Corporation found signs of disturbance in the winding insulation, they realized that it was time to perform a major maintenance. The company decided on a rewind. Authors were invited to participate in a field test. Calpine wanted to find out what has caused the disturbance. Some samples of the affected windings were examined. There seems to be various stages of degradation.

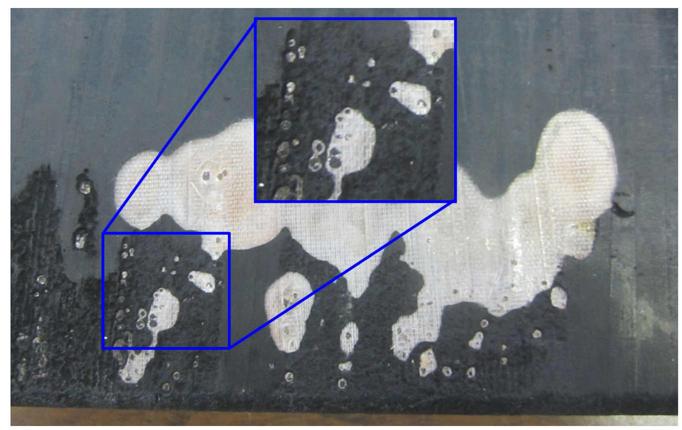

Fig. 1 – Patches of insulation damage on winding. Close-up highlights pinholes formed in the conductive carbon paint.

It is hypothesized these were related hot spots developed in the stator, caused by Eddy current loops, formed when damage occurs between the insulation and the neighboring laminated steel plate. The hot spots reduced the performance of the insulation and PD subsequently occurred, eroding further the carbon paint. Furthermore, mica insulation also suffered from damage. PD activities would not have sufficient energy to puncture the mica. Therefore, another failure mechanism might be at work: vibration sparking. Such process is defined by excessive vibration occurring in the slot so that the carbon paint – normally maintaining ground contact to the stator – failed and high voltage appears at some of those disturbed locations and the air breaks down to form a plasma. Fig. 2 illustrates the concept. For the other side of the vibrating part, the plasma lost contact with its current source. This is a powerful source of electro-etching, an industrial process used to etch hard material like ceramics. If this process continues undetected, soon it would destroy completely mica insulation, leading to an unplanned outage (see Fig 3).

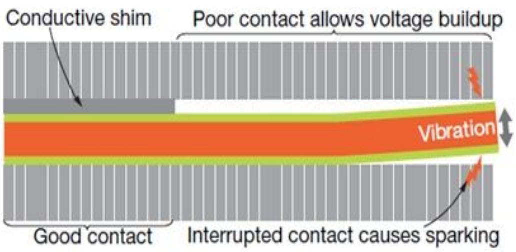

Fig. 2 – Vibration sparking conceptualization.

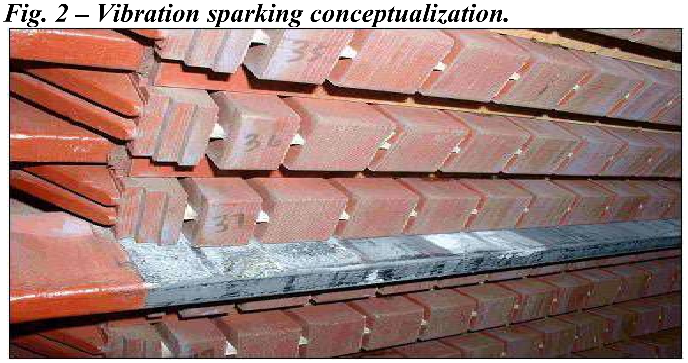

Fig. 3 – Complete winding insulation became destroyed at another power plant suspected to have similar problem.

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 fiber at a small distance, which forms a cavity. When a laser beam with matching center wavelength is launched into the cavity, it gets reflected and goes through a 180 degrees phase shift, giving rise to two interfering beams and a dense spectrum of fringes as shown in Fig. 4.

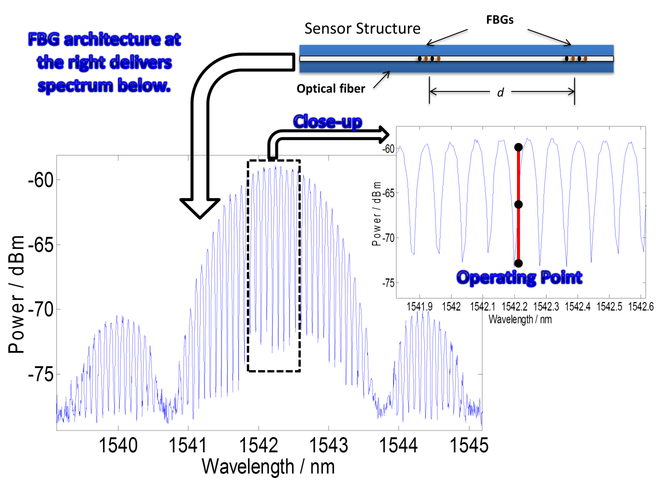

Fig. 4 – Correlation between fiber optic structure and resulting spectrum where a selected fringe will be monitored for changes due to both static/dynamic stain and temperature.

The larger the cavity length, the denser will be the fringe pack with steeper 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. This operating point stays locked using both the laser current (LC) and the thermoelectric cooler (TEC) analog controls of the laser. When vibration occurs, the fringe pattern will be moving right and left, it forces the operating point to ride up and down the slope, translated into intensity changes. The changes accurately reflect the actual vibration that is occurring. Since the cavity is also affected by temperature, a self-calibration algorithm was introduced to re-establish the operating point and such compensation delivers an indirect method to measure temperature (Fig. 5).

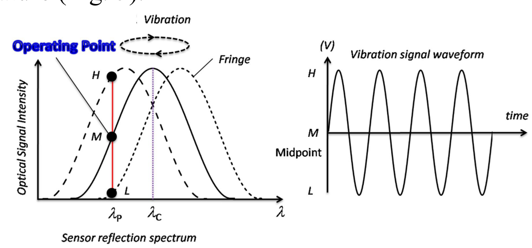

Fig. 5 – Correspondence between fringe oscillation and resulting vibration.

Another invention linked to the cavity is the long gauge technology. By splicing a length of single-mode optical fiber on to the cavity, a new cavity sprouts between the two matching FBGs cavity and the interrogation system connector. Said connector triggers a Fresnel broadband reflection, enabling a thin in-slot vibration distributed sensor to be used in a field test inside a gas-fired generator.

SENSING HOT SPOTS AND VIBRATION

There are two types of sensors. One of them makes use of the Brillouin technology where two laser beams are fed into the same fiber optic loop and both lasers have very close center wavelengths that are made to beat against each other, generating a beating frequency. This beating frequency is sensitive to any index changes in the fiber as hot spots. Hence, it is able to report their location along the sensing fiber. The temperature sensor forms a loop inside the slot. In the middle of it; a single point temperature (yet distributed for vibration) sensor is installed (see Fig. 6). The top slightly bluish fiber together with the bottom yellow fiber are the Brillouin temperature sensing loop; the dark hexagon houses the temperature sensing cavity with vibration sensitivity for the whole length of the fiber extension. The whole length of the slot, which measures five meters long, has its vibration captured. The single point temperature measurement provides a temperature reference for the Brillouin hot spot temperature sensing measurement.

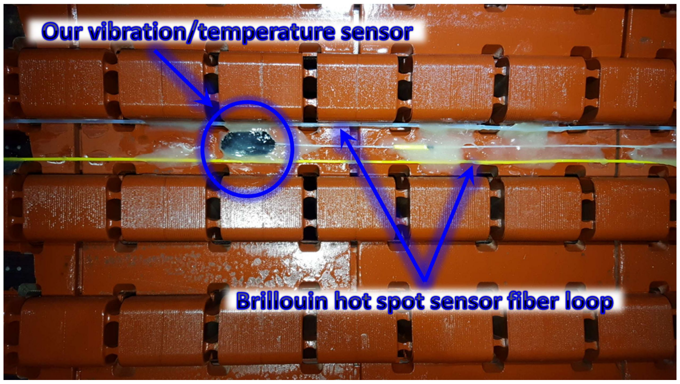

Fig. 6 – The in-slot vibration sensor installed between the Brillouin temperature sensing fiber loop (U-turn not shown).

DETAILS OF THE FIELD TESTS

Besides the Brillouin hot spots sensor and the in-slot vibration sensor, two other cavity vibration sensors were installed. One is coupled with the end winding lead and another one with the end winding bus; all are done on the neutral phase of the generator. All sensing fibers are protected by Teflon tube where the sensor tip is housed in a molded PEEK package (see Fig. 7). It is an open face design. The same sensor was also used to measure vibration inside the transformer. The long gauge vibration sensor is a wideband sensor, able to detect frequency ranging from 10 Hz to 1 kHz for standard version and 5 Hz to 2 kHz for extended sensing range (see Fig. 8).

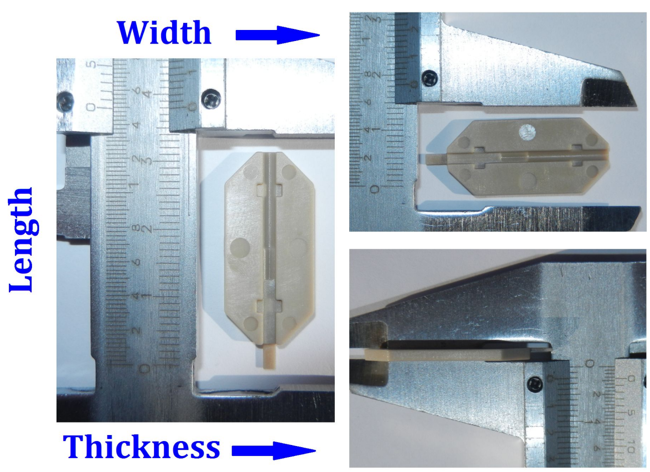

Fig. 7 – The vibration sensing cavity housed inside a PEEK package.

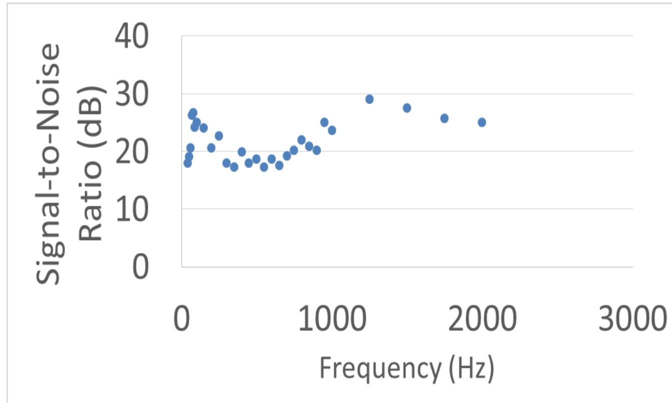

Fig. 8 – The in-slot vibration sensor bandwidth can even be extended from 10Hz~1kHz (standard) to 5Hz～2kHz.

IN-SLOT VIBRATION RESULTS AND DISCUSSION

The in-slot vibration sensor which has been installed onto the wedge (see Fig. 6) gave a very clear vibration response as illustrated in Fig. 9.

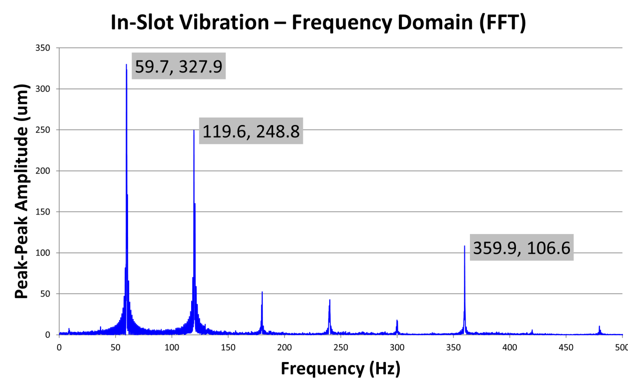

Fig. 9 – FFT showing in-slot vibration characteristics.

We observed a strong line frequency (1xLF) vibration frequency together with a strong two times line frequency (2xLF) component. The 1xLF component measures 15 mil peak-to-peak and the 2xLF component measured 10 mil peak-to-peak. This was very high compared with previously experienced 2 mil peak-to-peak in the end winding vibration of coal-fired generators. It is noted that there exist some harmonics which rolled off normally but then showed a strong peak at 6xLF. In this generator design, the bearing is coupled onto the frame which became incorporated into the slot vibration. Concern was expressed to Calpine as this seems to be slightly too high.

VIBRATION IN THE END WINDING LEAD

One single point vibration sensor was installed at the end winding of the neutral lead as depicted in Fig. 10. The photograph at the right shows the end winding conductor before the sensor installation where the colored circles pinpoint where the two additional discrete sensors would end up coupled with.

Fig. 10 – Two discrete sensors coupled at two different locations of the neutral bus of the phase C conductor.

The end winding lead sensor also showed strong vibration spectrum in both 1xLF and 2xLF. There were hardly any harmonics. The 1xLF component measured 15 mil peak-to-peak and the 2xLF component measured 11 mil. They are higher than what we expect but consistent to the in-slot measurement (see Fig. 11).

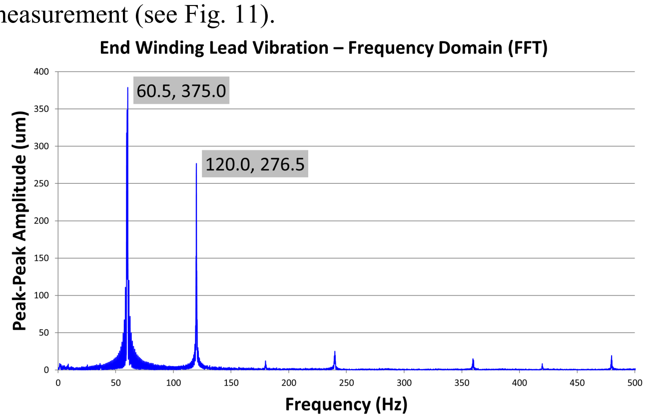

Fig. 11 – End winding lead frequency domain.

VIBRATION AT THE NEUTRAL END WINDING BUS

A third vibration sensor was mounted on the neutral end winding bus (see Fig. 10). Once again, the vibration observed here is also consistent as depicted below in Fig. 12.

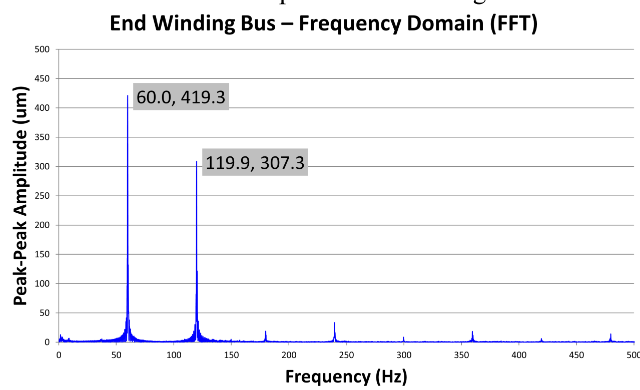

Fig. 12 – End winding bus frequency domain.

Larger vibration amplitude is shown: 1xLF component measured 16.5 mil peak-to-peak and 2xLF measured 12.1 mil peak-to-peak. It seems that gas-fired generator vibrates much more than the coal-fired generators. Plant experts informed all participants of the field test that it may be related to the generator design where the bearing is coupled to the frame. Vibration was so strong in similar machine that cracks developed.

AIR COOLING INSIDE THE GAS-FIRED GENERATOR

The gas-fired generator involved in the field test was manufactured by Siemens. Fig. 13 shows a conceptual diagram of the cooling air radial flow. There are resistance temperature detectors (RTDs) installed at different places of the air path. We will compare our measurement with those coming from the supervisory control and data acquisition (SCADA).

Cooling air flows through many cooling ducts placed approximately two inches apart from each other. Blue arrows are meant to represent cooler air entering the core. As it flows through the ducts, the air progressively relieves the stator core of its heat (yellow arrows) and it ends up evacuated (red arrows) via the main central exhaust.

Since RTDs carry conducting material, they are mainly installed in the grounded core. This field test represented the first time where in-slot vibration and hot spot measurement were performed.

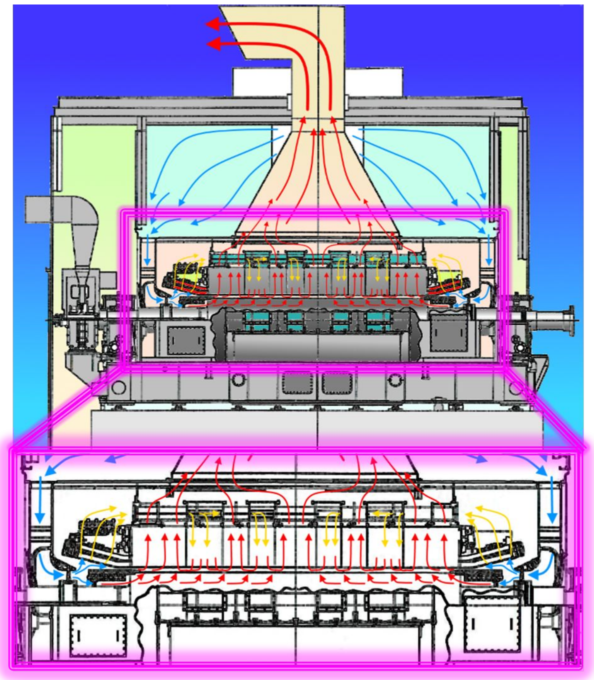

Fig. 13 – Siemens Westinghouse AeroPac I generator with emphasis on the radial airflow via colored arrows.

IN-SLOT AND END WINDING TEMPERATURES

The temperature distribution inside the slot was measured by the Brillouin fiber optic loop sensor. The gathered data brought up a wave-like distribution as demonstrated in Fig. 14. The distribution is not flat; the cooling airflow did not form a perfect balance. The temperature extrema were less than two degrees C apart, positively assuring the lack of hot spots.

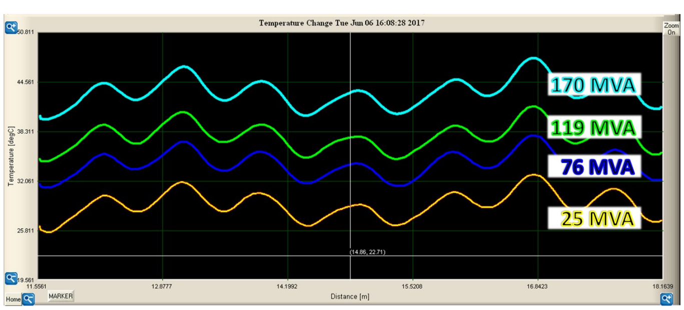

Fig. 14 – Temperature profiles at different loading intensities.

We tried to line up the temperature profile with the layout of the air ducts by wrapping over at the middle. Valleys coincide very well with the air duct exhaust and the top peak always occurs in the middle between two air ducts where there are minimum cooling airflow (see Fig. 15). The difference between peak and valley is consistent at different loading levels.

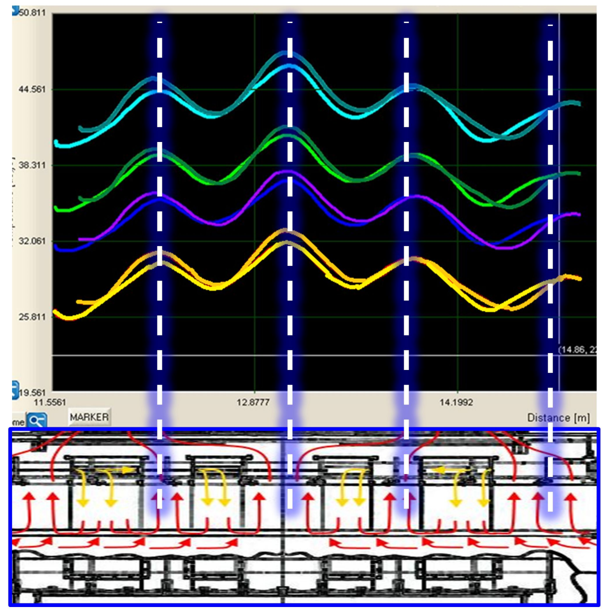

Fig. 15 – Temperature profile line-ups with the air duct locations.

Fig. 16 shows the temperature measurement of the in-slot sensor. The red plot indicates the coarse temperature reading of 70 degrees C at a loading of 170 MVA. The blue line shows the fine temperature variation over a period of 10 minutes. The sensor was able to detect temperature changes down to 0.1 degree C.

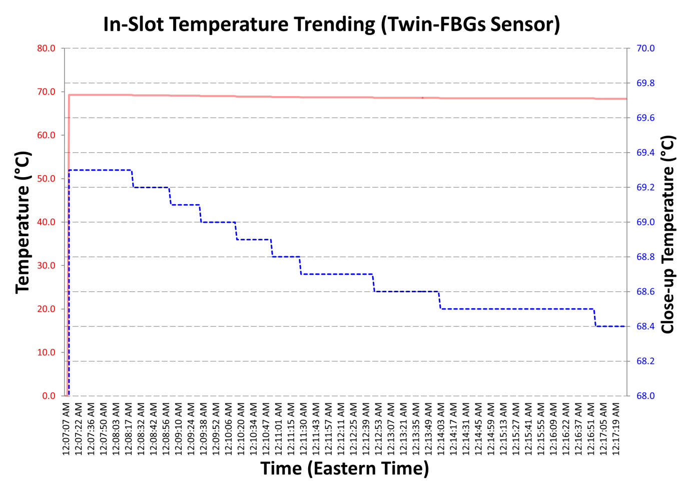

Fig. 16 – In-slot temperature measurement for 10 mins.

The end winding lead (Fig. 17) showed a temperature consistent with the slot as well as the end winding bus (see Fig. 18). All of them read close to each other, there does not seem to be any problem.

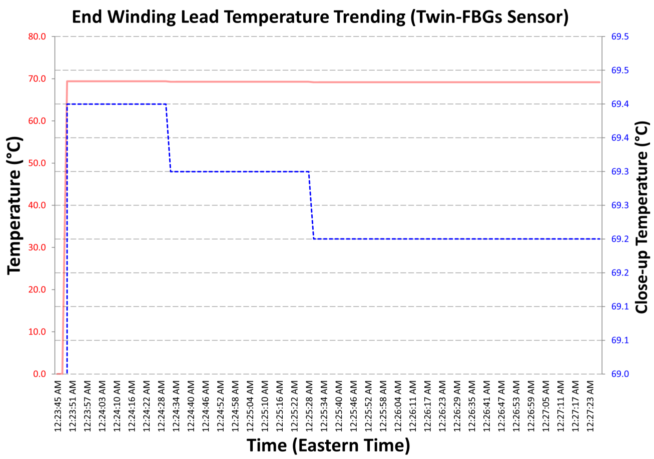

Fig. 17 - End winding lead temperature measurement for about five mins.

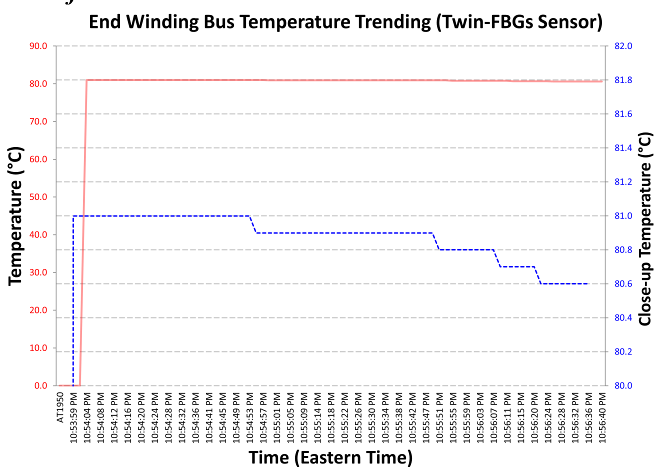

Fig. 18 – End winding bus temperature measurement for about three mins.

HOW TEMPERATURE MEASUREMENT IS AFFECTED BY PLACEMENT OF THE SENSOR

The temperature sensing fiber optic loop was deliberately placed asymmetrically. Referring to Fig. 19, the top sensing arm was set right at the foot of the wall where it would be affected by a shadowing effect. The cooling air would flow slightly outward in contrast to the other arm of the loop, which was placed close to the center of the slot, free from the shadow effect. The top represents the worst case.

Fig. 19 – Top view of the core slot where the two Brillouin sensing arms are laid onto the wedge.

The temperature difference between the two arms was found to be less than 1.1 degrees C (see Fig. 20). It is uncertain whether it is related to the distance from the vent hole.

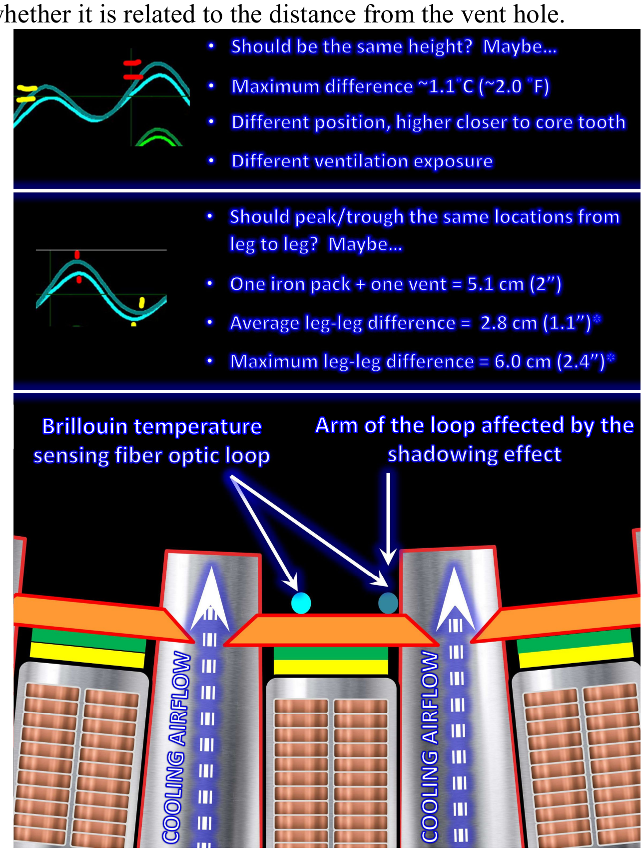

Fig. 20 – Diagram of a section of the stator core with slots filled with coils, ripple springs, wedges, etc.

CONCLUSION

After the rewind and the installation of the distributed temperature and vibration sensor, no hot spots occurred to be pinpointed. The temperature inside the slot is a reasonable 70 degrees C. The aforementioned temperature readings from the fiber optic sensors are consistent with the RTD ones in the core as displayed in Table 1. Consistency is seen between core, the in-slot as well as the end winding regarding the RTD temperature measurements.

Tab. 1 – Maximum temperature correlation with generator load using control room data issued from the RTD readings.

Load	Cold Air	Hot Air	Embedded	Av. Trough*	Av. Peak*
170 MVA	30.6˚C	64.4˚C	78.1˚C	63.9˚C	67.0˚C
119 MVA	28.6˚C	57.8˚C	64.1˚C	58.3˚C	61.3˚C
26 MVA	21.6˚C	45.6˚C	45.3˚C	49.9˚C	52.7˚C

The temperature experimental data shows a linear correlation with the load applied on the generator

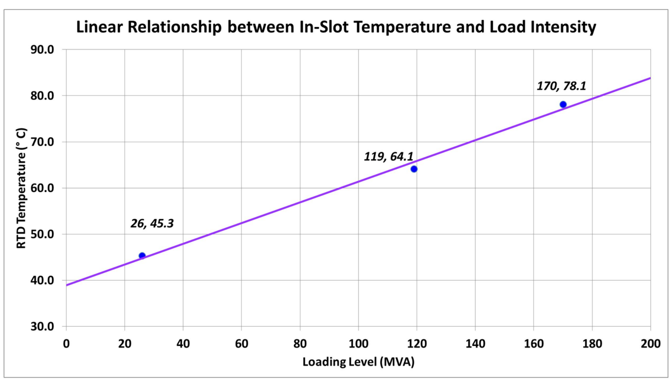

Fig. 21 – Temperature linear relationship between in-slot and load applied to the generator.

FUTURE WORK

Another field test has been planned for a hydrogen-cooled gas-fired generator located in Texas. It is planned to measure hot spots using a new array of vibration and temperature sensors.

REFERENCES

Kung, P., Idsinga, R., Vera-Durand, H.-C., Comanici, M.I., Yang, C.S., Fu, J.B., June 2016, "Online Detection of Windings Distortion in Power Transformers by Direct Vibration Measurement Using a Thin Fiber Optic Sensor," IEEE Electrical Insulation Conference (EIC), pp. 576-578.

Mohammed, A. and Djurović, S, May 2017, "FBG Thermal Sensing Features for Hot Spot Monitoring in Random Wound Electric Machine Coils," IEEE Sensor Journal, Vol. 17, pp. 3058-3067.

Tetreault, A., 2008, "End-Winding Vibration in Large Rotating Machines," 74th Annual International Doble Client Conference, pp. 1-14.

VibroSystM, 2010, "On-line Vibration and Temperature Direct Measurement on High Voltage Devices Using Fiber Optic Sensor Technology," Condition Monitoring and Diagnostics (CMD) Conference Proceedings.