On-line Vibration and Temperature Direct Measurement on High Voltage Devices Using Fiber Optic Sensor Technology

***Abstract*—In the past 25 years of VibroSystM's field of experience in installing its various sensors on generators, it has always been imposed by utility personnel that cabling or sensors installed on their generators be positioned to avoid the high voltage part of the generator. With VibroSystM's innovative design, the fiber optic accelerometer(FOA) and fiber optic temperature sensor(FOT) allows the sensor to be coupled directly to the high voltage end-windings, brush gears, circuit breakers, or any other parts in the high voltage, highly explosive gas environments, where the traditional hardwire transducers cannot be safety mounted. This technology breakthrough provides direct measurement of the local vibration and temperature, safely obtains accurate quantitative signals via fiber optics, and thus greatly enhances utilities' ability to access the condition of high-voltage equipments. The benefits and effectiveness of this technology will be discussed in this paper.**

Keywords- component, end-windings, vibration, temperature, high voltage, fiber optic, accelerometer, generator monitoring, sensor

I. INTRODUCTION—FIBER OPTIC ACCELEROMETER

Vibration monitoring has long been the primary strategy implemented on turbo-driven generators in order to ensure some predictive maintenance capability and thus prevent major failures. Shaft displacement probes are commonly used to monitor the radial vibration of the shaft, in X and Y axis, and hence attempt to keep the vibration levels below existing or manufacturer specified standards. Different technologies exist in the field (capacitive, inductive, piezo-electric etc) and have shown to be usually reliable. However, these probes are mainly installed either in air or in oil, away from electrical and environmental hazards. End-winding vibration monitoring presents a particular series of challenges. The least of which, maintaining reliability while being exposed to high voltages, temperatures ranging from 60ºC to 125ºC and most importantly, making sure the measuring chains does not affect the end-winding in any way and is safe for personnel. In recent years, fiber optic technology has produced a new series of sensors, which allow for installation directly on the end-winding. Because of their electrical insulation, they are not affected by the high magnetic fields and do not cause any harm to the Unit itself. The FOA-100 (one axis) and FOA-200 (Dual-axis) Fiber Optic Accelerometers were designed by VibroSystM specifically for this purpose. They have proven to be an invaluable part of end-winding vibration monitoring strategy for an increasing number of utilities and OEMs in the last few years. Their reliability and accuracy have provided critical data to users and have, in many cases, allowed utilities to invoke warranty claims as end-winding vibration was found to be beyond acceptable levels.

II. INSTALLATION CONSIDERATION

Many different issues are involved in planning the installation of fiber optic accelerometers. Although these sensors are designed for the harsh environment present in large turbo-driven generators, specifications must be taken into account before installation can begin. Parameters such as maximum temperature, maximum hydrogen pressure, distance between sensor head and penetration flange etc. In addition, position of sensor is limited to the minimum bending radius of the fiber optic cable.

FOA-100 & FOA-200 sensors can be installed on any bar of the stator winding. However, it is well known that some stator bars are more vibration prone than others. The bars most likely to show vibrations are those connected to the terminal of each phase. Unlike other bars, these high-voltage bars are not mechanically interlocked on the lower plane. It is also recommended to select and monitor the vibrations on these bars, as these are also likely the first to fail from degraded insulation. In addition, usually the largest amplitude of vibrations is found on the bars located closest to the air gap, called top bars. These vibrations result from a combination of the alternating magnetic field in the machine and the natural resonance frequency of stator windings. It is highly recommended to use the manufacturer supplied drawings to identify the individual coils. In some cases, the known problem areas and specific bars can be targeted for monitoring.

To correctly monitor the occurrence of vibrations, the monitoring of at least one bar per phase in the radial axis of vibration is recommended. To monitor the second most common axis of vibration, the tangential, a single accelerometer on each end of any high-voltage bar is sufficient. On a typical turbo-generator with two-coil windings, a total number of 14 FOA-100E accelerometers: 6 on each end of the high-voltage bars for radial displacement monitoring, plus one on each end for tangential displacement monitoring. In the case of

FOA-200, 12 sensors are sufficient. Figure 1 represents a typical layout of FOA accelerometer.

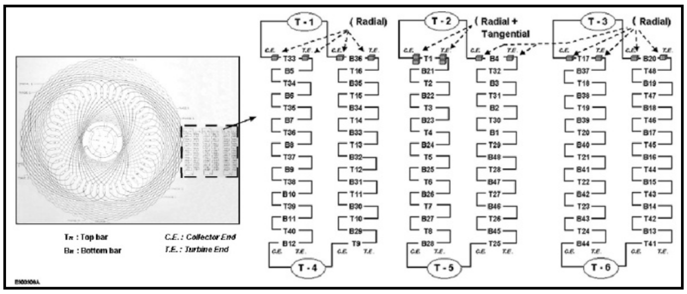

Figure 1 Stator Winding Diagram and location of accelerometers

Figure 2 is an example of the FOA accelerometer.

Figure 2 Fiber Optic Accelerometer: FOA-100, FOA-100E and FOA-200

III. CASE STUDIES

Case Study 1 – Consumers Power [1]

An early application of the VibroSystM sensors was made on two units by Consumers Power at their Campbell plant. One unit was a relatively small generator installed in 1962 and rated 156 MVA; this unit has a direct hydrogen-cooled stator winding. The second unit was a very large 1025 MVA generator installed in 1980; this generator has a water-cooled stator winding. Two different manufacturers were involved.

Oddly, while the VibroSystM detectors on the larger unit are recording very low endwinding vibration levels, the smaller unit is experiencing significant vibration. This small generator will have low electromagnetic forces driving endwinding vibration, and thus perhaps the endwinding vibration is driven at least partially by the stator core. The minimum readings of the detectors are in the range of 125-150µm (5-6 mils), but trend upward with time. When vibration levels have reached about 250µm (10 mils), the endwindings must be reworked. The repair attempts thus far have not been completely successful in permanently containing the vibration. Thus, the detectors are serving as a powerful tool to monitor vibration and identify when rework becomes necessary on the endwindings.

The larger unit has very high electromagnetic forces driving vibration of the endwindings. However, the endwinding support system is functioning well, and vibrations levels are low, near 50µm (2 mils). Again, the detectors are performing the intended purpose, i.e., monitoring the condition of the endwindings on a very large generator with very high forces driving vibration of the endwindings.

Case Study 2 – South Carolina Electric and Gas [2]

Upon startup of a new 405 MW unit, the generator had very high vibration levels throughout the frame and stator endwindings. Vibration levels were sufficiently high to break a foundation bolt within a short time, damage the IP/LP turbine cross-over compensator (expansion joint), and fracture stator endwinding expansion spring plates. Noise levels were sufficiently high to preclude standing any period of time under the generator frame even with ear protection. After less than 3 years of service, a stator winding phase connection ring fractured. The resulting three phase have severely contaminated the generator. Repairs required three months to complete.

Attempts were made to reduce endwinding vibration levels by making minor connection ring support modifications, with limited success. In order to quantify the levels of endwinding and connections vibration, VibroSystM detectors were added to the endwindings: 6 on the drive end stator endwindings, 6 on the non-drive end stator endwindings, and 6 on suspect connection ring elbows. These detectors recorded high levels of vibration, in excess of 250µm (10 mils), predominantly on the non-drive end windings.

Based on the data from the VibroSystM detectors and other data on the generator and turbine, it was concluded the only permanent fix would be replacement of the stator. A major issue was resonance vibration of certain non-drive end components at 2 times running frequency (120 Hz). This was confirmed by bump testing with the unit off-line. A new stator designed specifically for 60 Hz operation has been ordered and will be installed on this generator in 2010.

IV. CONCLUSION

Stator endwinding vibration has been a major deterioration concern on large turbine-generator windings for 50 years. Until recently there has not been a safe, convenient and reliable method for measuring vibration magnitudes and frequencies in the high voltages which exist in the endwindings.

Fortunately, there is now available at least one device that can measure local vibration and safely transmit accurate quantitative signals via fiber optics to instrumentation outside the generator casing.

Because of the high costs associated with ongoing problems being experienced with endwinding vibration, the availability of these devices to the industry is extremely important. This equipment should be of great assistance to generator designers but also to personnel responsible for operating and maintaining large turbine generators. Because of the vital need for such capability, application of such devices should become wide-spread.

It is unlikely that application of endwinding vibration measuring equipment will become as universal as, for example, resistance temperature detectors. However, it can be expected that these devices will eventually become standard monitoring instrumentation on all large generators, as well as common on smaller generators.

Extract from the paper "Vibration Detection Instrumentation For Turbine-Generator Stator Endwinding" by Clyde V. Maughan.

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I. INTRODUCTION— FIBER OPTIC TEMPERATURE SENSOR

Temperature is a key parameter to monitor in assessing the condition of an electric generator. Many overheating issues result from excessive current or vibration and friction on the unit. Excessive current and friction can have a negative impact on the life span and performance of the slip-ring and brushgear in particular. It is therefore important to monitor these two closely linked pieces of equipment.

The case at hand studies the Rapide-2 Power Generating Station, located in Quebec, Canada. It began operations in 1954 and underwent a generator refurbishment program in 2003. The station is comprised of four (4) generating units. On unit 23, overheating of the new slip-rings inside the collector compartment was suspected. To collect more precise data, on-line slip-ring and brushgear temperature sensors were installed. An abnormal temperature rise of the brushgear was detected.

A. Slip-Ring Overheating On Unit 23

Generator refurbishment began in 2003 with each of the four (4) units being overhauled in sequence. During commissioning tests on a newly refurbished unit, it was suspected that there was overheating in the slip-ring area. Temperature measurements therefore had to be taken. The first measurements were taken using temporary wireless rotating contact sensors RTDs (resistance temperature detectors), installed directly on the rings. A temperature of 145 °C was obtained, confirming that the slip-rings were overheating (maximum accepted: 125°C)[3]. Plant personnel wanted to replace the temporary rotating contact sensors (RTDs) with a permanent alternative. Hydro-Quebec sought VibroSystM's advice on the matter; VibroSystM proposed a different type of sensor.

B. Rugged High Temperature Sensor

Common sense suggests slip-ring and brushgear issues are closely intertwined. For example, Mr. Douglas E. Franklin from BC Hydro, points out in his article *Mechanical Aspects of Brushgear*, published in the August 2007 Issue of Hydro Review magazine that: "It is important to look at all aspects of the collector-brushgear assembly systems when trying to identify the root cause of problems with brushgear. In particular, the grooves in the slip ring can affect brushgear performance. Because the impedance of the rotor field winding is unlikely to change, the additional voltage drop will be in the brushgear. The additional power output of the exciter will be dissipated by the brushgear in the form of heat, and the most likely place for this to occur is at the contact face between the brush and the slip ring."[2]

Therefore to monitor the brushes, a contact sensor designed for harsh environments, was installed. In this way, long-term accurate and valid temperature readings could be gathered even if the area sustained significant dirt and oil build up over time. As the brushes are points of high voltage on the generator, the material of the sensors was an important consideration. It was important that the contact sensor be non-metallic and non-conductive.

VibroSystM therefore used its Fiber Optic Temperature sensor, FOT (see figure 3), whose sensor head and cabling is free of any conductive materials and immune to EMI (electromagnetic interference). The temperature measuring range of this sensor is 0 - 200°C (32 - 392°F), which fits the criteria, given that the maximum accepted temperature according to the IEEE is 125°C[3].

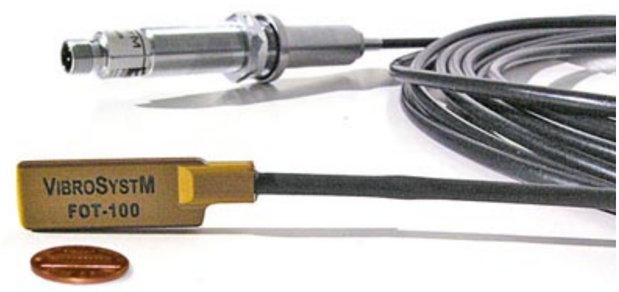

Figure 3 FOT small sensor head: immune to EMI, non-metallic and electrically non-conductive.

II. INSTALLATION

Two (2) Fiber Optic Temperature sensors were installed on the upper and the lower brush guides of Unit 23.
Some bolted brackets secured sensors head in place. See figure 4

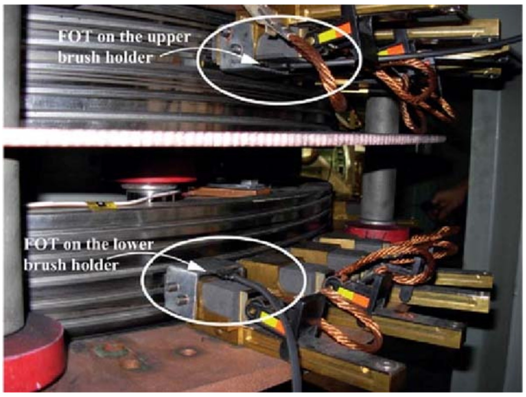

Figure 4 Installation of Fiber Optic Temperature sensors on Unit 23

III. RESULTS AND ANALYSIS

The FOT allowed personnel to collect data on the brushes while the machine was fully operational. The sensors also measured higher temperatures as current increased. This temperature increase was expected as it is a well known occurrence. The readings did help to validate the functionality of the FOT. To be certain, these results were cross referenced with the RTD data. Both data collection methods were consistent.

At full load the temperature exceeded the OEM's suggested maximum limit. There was once again a consistency amongst the data collected from the three different types of probes. The OEM recognized the validity of the results, which pointed to an overheating issue in the slip-ring compartment on both brushgear and slip-rings. The OEM acted accordingly, working with the utility to solve the problem. Figure 5 shows temperature readings from the three (3) types of sensors after the OEM corrected the overheating problem.

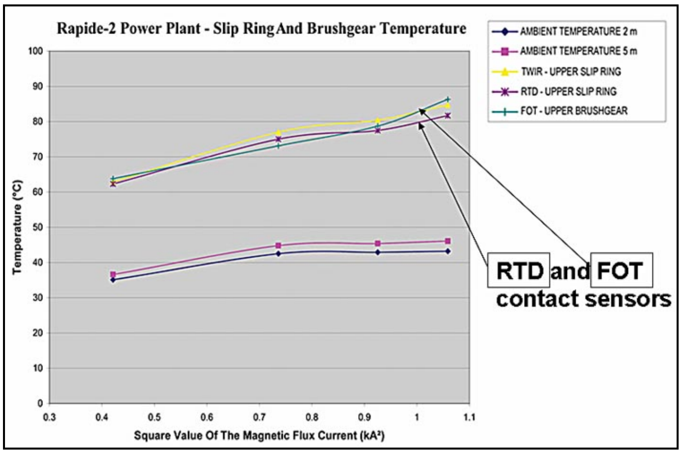

Figure 5 This graph displays the temperature measured by contact sensors, on the upper brushgear after corrective actions were taken to resolve the overheating problem

IV. SUMMARY

Brushgear monitoring allows prevention of breakdown, and keeps in check the high cost of equipment replacement by supplying personnel with precise data on collector compartment temperature.

After refurbishment over the last few years of all units at Rapide-2 and Rapide-7, the installation engineer noticed an increased in temperature inside the exciter casings, a situation which can lead to failure and force unscheduled outages. To further study the temperature inside the exciters, Hydro-Quebec has thus expressed an interest in the installation of two FOT sensors on the exciters insulated brushgear, one on the lower ring and the second on the upper ring. Insulated and uninsulated brushes are submitted to the same voltage, but there is no current flow in insulated brushes. Despite this difference, as they are in contact with the rings, insulated brushes still transmit all temperature variations in the lower and upper rings. Preliminary testing showed a difference of 4°C between insulated and uninsulated brushes, the lower temperature in insulated brushes being explained by the absence of current flow. FOT sensors installed on insulated brushgear proved to be more apt to produce accurate results as the temperature of insulated brushgear is not altered by variations in current flow. In uninsulated brushes, fluctuating current flow induces variations in temperature which are not necessarily in direct relation with the ring temperature. With the installation of two FOT sensors on insulated brushgear, Hydro-Quebec has gained a reliable tool for sustained monitoring of temperature of the actual brushes behaviour inside generator exciters.

V. CONCLUSION

Measurement of brushgear can now be obtained safely by utility personnel, in a hazardous environment, with permanently installed sensors, while the machine is fully operational and producing electricity. The system used in this case was designed as a permanent solution to brushgear temperature monitoring, however it also can be used for any other parts in the high voltage, highly explosive gas environments, like high voltage end-windings, circuit breakers, etc.

REFERENCES

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