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Determination of Hot Spots in Gas Generators Using Brillouin Based Fiber Optic Distributed Sensor

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SUMMARY

Modern combined cycle power plants, with state-of-the-art gas turbines and steam turbines coupled to air-cooled or H_2-cooled electrical generators, are highly refined technology concepts offering unmatched excellence in operation, reliability, and environmental friendliness. While generator core failures aren't common, their potential impact is up to the catastrophic level. One yet-unsolved issue is the occasional development of hot spots in the stator core, where thousands of insulated carbon steel laminates are tightly pressed and clamped together. The insulation between laminations tends to degrade in service, and foreign objects and impacts during regular maintenance outages can damage the insulation as well. Damaged insulation can cause large eddy currents to flow leading to core damage or forced outages as the hot spots proceed to heat up and damage the bar insulation. Presently, the only methods of identifying these hot spots require off line inspections like the ELCID, or the loop or ring flux test in conjunction with thermal imaging, but both of these tests offer challenges in correlating measured values to actual online temperatures, and neither one offers protection from emergent issues online. Current design practice does include the installation of several embedded RTDs in the core region, but these point-measuring elements are so few, and so limited in physical sensitivity range, that the probability of detecting a core issue with one is very small.

Brillouin scattering based distributed strain and temperature sensing (DSTS) provides an excellent opportunity for power generator applications, because it is unaffected by electromagnetic interference (EMI) and vibration.

This paper presents the results of generator stator temperature profile tests that used a DSTS product, and were performed in a Siemens air-cooled generator, a GE H_2-cooled generator, a Hitachi H_2-cooled generator, and a Toshiba H_2-cooled generator owned by Calpine Corporation. Hot spots only 1 cm in length can be detected by DSTS technology when the temperature change is over 30°C. The online temperature readings from the fiber optic lines compared well against the existing RTD readings. More importantly, beautiful data curves emerged which clearly demonstrated the stator zone-cooling temperature affects along the length of the fiber installed in these generators, and it's incredibly interesting given that we've never had this kind of data before. DSTS technology has proven to be an efficient and cost-effective solution to monitor temperatures in electrical generators.

KEYWORDS

Gas generator, Hot spots in stator core, Fiber optic distributed sensor, ELCID, RTD, EMI

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1. Introduction

Modern combined cycle power plants, with state-of-the-art gas turbines and steam turbines coupled to air-cooled or H_2-cooled electrical generators, are highly refined technology concepts offering unmatched excellence in operation, reliability, and environmental friendliness. While generator core failures aren't common, their potential impact is up to the catastrophic level. One yet-unsolved issue is the occasional development of hot spots in the stator core, where thousands of insulated carbon steel laminates are tightly pressed and clamped together. The insulation between laminations tends to degrade in service, and foreign objects and impacts during regular maintenance outages can damage the insulation as well. Damaged insulation can cause large eddy currents to flow leading to core damage or forced outages as the hot spots proceed to heat up and damage the bar insulation. Presently, the only methods of identifying these hot spots require off line inspections like the ELCID, or the loop or ring flux test in conjunction with thermal imaging, but both of these tests offer challenges in correlating measured values to actual online temperatures, and neither one offers protection from emergent issues online. Current design practice does include the installation of several embedded RTDs in the core region, but these point-measuring elements are so few, and so limited in physical sensitivity range, that the probability of detecting a core issue with one is very small.

Brillouin Optical Time-Domain Reflectomers (BOTDR) or Brillouin Optical Time-Domain Analyzers (BOTDA) have been used for many years as a means to perform distributed temperature sensing using optical fibers as sensors [1, 2]. Both methods measure the local Brillouin spectrum of the fiber, and use the dependence of the Brillouin spectrum on temperature and strain to measure either temperature or strain or both temperature and strain through

$$\nu_B(T_0,\varepsilon)=C_\varepsilon(\varepsilon-\varepsilon_0)+\nu_{B0}(T_0,\varepsilon_0) \quad (1)$$

$$\nu_B(T,\varepsilon_0)=C_T(T-T_0)+\nu_{B0}(T_0,\varepsilon_0) \quad (2)$$

where C_ε and C_T are the strain and temperature coefficients, and ε_0 and T_0 are the strain and temperature corresponding to a reference Brillouin frequency ν_{B0}. From Eqs. 1 and 2, it can be concluded that to have accurate measurement of Brillouin spectra is essential to get high accuracy of temperature and/or strain, and a short pulse duration must be used to have high spatial resolution. The energy inside the short pulse in time domain will create a wide spectrum in the frequency domain. This causes inaccurate measurement of the Brillouin spectra, which results in inaccurate measurement of temperature and/or strain. To get high spatial resolution and highly accurate measurements of temperature and/or strain, one of the authors [3] demonstrated theoretically and experimentally that the Brillouin interaction of probe and pump beams in the fiber includes both pump–dc and pump–pulse interactions in the probe-pump Brillouin sensor system. The dc component can be separated into two portions by their phases after propagating through the EOM (Electro-Optic Modulator). The dc part outside the pulse length interacting with the pump gathers information from all along the fiber and loses the spatial information, whereas the interaction of the pump with the dc component inside the pulse length is coherent with the pump–pulse interaction, which amplifies the Brillouin signal significantly. Based on coherent probe-pump interaction technology, our Brillouin scattering based distributed strain and temperature sensing (DSTS) provides accurate local temperature and strain information at a high spatial resolution by controlling depletion of the pump beam resulting from the strong coherent interaction of the pump and the probe in the fiber. This provides an excellent opportunity for power generator applications, because it is unaffected by electromagnetic interference (EMI) and vibration.

This paper presents the results of generator stator temperature monitoring tests that used a DSTS product, and were performed in a Siemens air-cooled generator, a GE oil + H_2-cooled generator, a Hitachi oil + H_2-cooled generator, and a Toshiba oil + H_2-cooled generator owned by Calpine Corporation. Hot spots only 1 cm in length can be detected by DSTS technology when the temperature change is over 30°C. The online temperature readings from the fiber optic lines compared well against the existing RTD readings. DSTS technology has proven to be an efficient and cost-effective solution to monitor temperatures in electrical generators.

2. Optical sensing cable installations

2.1 Installation in a Siemens open air-cooled generator

The overall goal of the experimental procedure was to assess the temperature monitoring capabilities of the DSTS technology with the sensing medium of optical fibers located on the stators. To achieve this goal, field tests were conducted in a Siemens air-cooled generator in Hermiston, OR, USA, a GE oil + H_2-cooled generator in Hidalgo, TX, USA, a Mitsubishi oil + H_2-cooled generator in Fore River, MA, USA, and a Toshiba oil + H_2-cooled generator in Middletown, CA, USA operated by Calpine Corporation in October 2017, June 2018, October 2018, and November 2018 respectively.

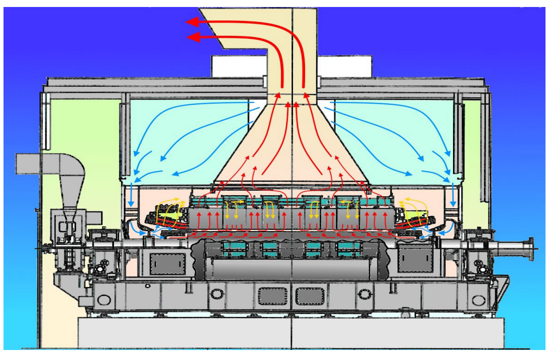

Fig. 1. Siemens Westinghouse – AeroPac I – Open Air cooled generator

Fig. 2. Optical sensing cables were glued on the stator of Siemens Open Air Cooled generator

A proof-of-concept application was installed firstly into Calpine's Hermiston CTG1 Siemens Westinghouse – AeroPac I – Open Air Cooled generator as shown in Figure 1. From Eq. 1, to avoid strain effects on the sensing fiber caused by thermal expansion of stator, the sensing fibers were installed inside a Teflon tube to become optical sensing cables. These were glued on one stator slot shown in Figure 2. The results from this application show (in the next section) beautiful data curves which clearly demonstrate the stator zone-cooling temperature effects along the length of the fiber installed in the generator. It is incredibly interesting, given that we've never had this kind of data before. The results encourage us to have more applications on gas generators.

2.2 Installation in a GE oil + H_2-Cooled generator

To install sensing cables on stators efficiently, the sensing fiber is contained within high strength PEEK tubing that ranges in size from 0.8 to 1.5 millimeters outer diameter. This tubing is small enough so that it can be integrated into all generator slot sizes without modifications or design changes to the generator components. The tubing can also be installed anywhere within the slot area, between top and bottom coils, on top of the top coil, or on the stator wedge surface. At certain locations a proprietary component is added to the tubing to compensate for relative thermal expansion differences between the optical fiber and generator components, which enables measurement of true temperature or strain. The PEEK tubing can be placed in direct contact with the stator laminations, stator coil groundwall, or both simultaneously. The 2nd DSTS application for a power generator with this kind of optical sensing cable was installed into Calpine's Hidalgo CTG1 GE oil + H_2-Cooled generator as shown in Figure 3 that displays the sensing cable installed under the wedges in the base shim stock to cover two stator slots.

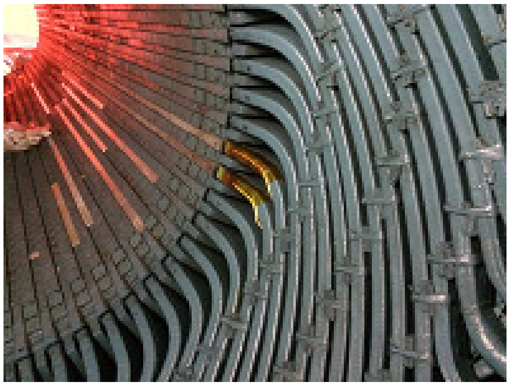

Fig. 3. GE oil + H_2-cooled generator

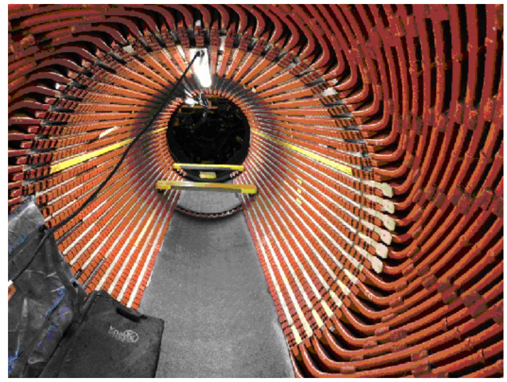

Fig.4. Hitachi oil + H_2-cooled generator

2.3 Installation in a Hitachi oil + H_2-Cooled generator

To find the locations of hot spots in a stator core where thousands of insulated carbon steel laminates are tightly pressed and clamped together is a challenge to "point" sensors that have very short gauge lengths, for example, 5mm, because the locations of hot spots in a stator core are not known *a-priori*. The major benefit of DSTS is continuous monitoring for all locations along a fiber up to 100km in length. The temperature changes due to hot spots can be detected, and their locations reported. Thus, it would be better to install longer optical sensing cable to cover more stator slots to detect hot spots. Figure 4 displays six stator slots to be covered by optical sensing cable in a Calpine's Fore River CTG12 Hitachi oil + H_2-Cooled generator.

2.4 Installation in a Toshiba oil + H_2-Cooled generator

There are 72 stator slots in a Calpine's Middletown Quicksilver STG16 Toshiba oil + H_2-cooled generator. In this case, 50 slots were covered by optical sensing cable, shown in Figure 5.

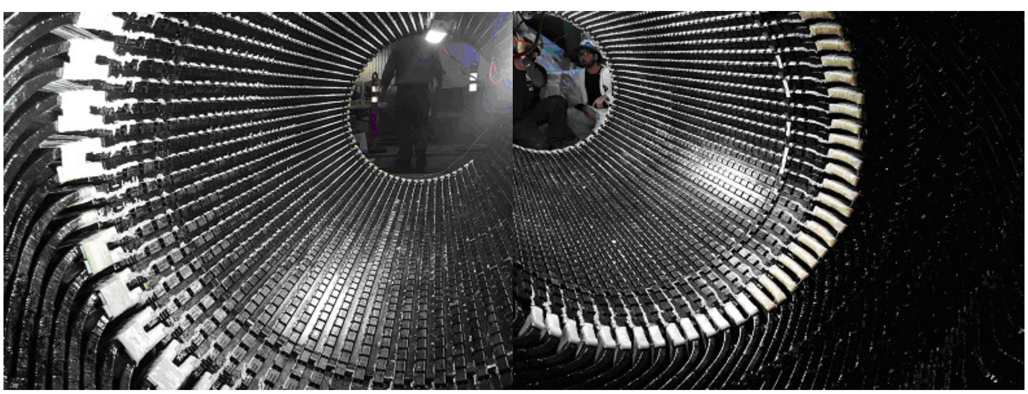

Fig. 5. Toshiba oil + H_2-cooled generator

3. Results

3.1 Siemens open air-cooled generator

Figure 6 displays temperature distributions along the sensing fiber installed on top of the stator wedges when the power loading increased from 25MVA to 170MVA, which clearly demonstrated the stator zone-cooling temperature affects along the length of the fiber.

Once online, temperature readings (referenced to a 21.5°C baseline) from the fiber optic line (DSTS) compared well against the existing RTD readings. The DSTS readings are hotter than the measured hot air (exhaust) temperature, indicating localized sensing of the temperature. The DSTS readings are cooler than the embedded RTD readings. This is expected because the embedded RTDs are radially deeper in the slots and are therefore less exposed to cooling airflow than where the DSTS sensor was. The wavy patterns in the temperature data along the length of the fiber correlate well to the different zone-cooled regions of the core, where the ventilation flow is moving radially inward or radially outward depending on the zone in the core. The temperature of each particular zone varies based on its flow path and the amount of heat the air flow has absorbed

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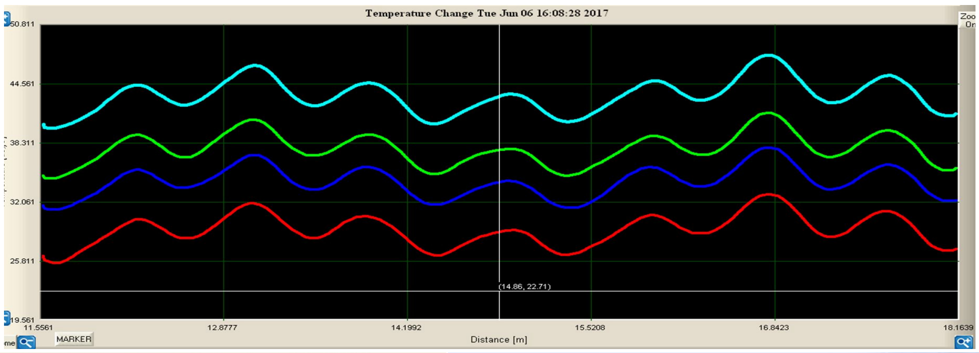

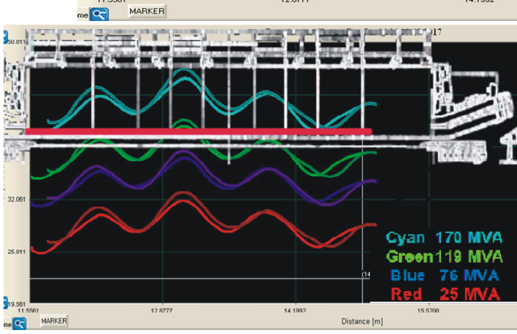

Comparison with RTDs and OZ DSTS Data

Load	Cold Air	Hot Air	Embedded	Av. Trough*	Av. Peak*	OZ DSTS
170 MVA	30.6˚C	64.4˚C	78.1˚C	63.9˚C	67.0˚C	68.0 ˚C
119 MVA	28.6˚C	57.8˚C	64.1˚C	58.3˚C	61.3˚C	62.2 ˚C
26 MVA	21.6˚C	45.6˚C	45.3˚C	49.9˚C	52.7˚C	53.5 ˚C

Fig. 6. Temperature distributions measured by DSTS and comparison between RTD and DSTS

In this test a BOTDA was used because it has higher accuracy than a BOTDR. A BOTDA requires the sensing fiber to be looped, and therefore the sensing fiber went through the same wedges twice. Thus, the loop-back point displayed by the cursor in the top of Figure 6 works as a mirror and the left and right sides of the cursor should be mutually mirrored. However, there is maximum temperature difference of 1.1˚C shown in the left of Figure 7. The right of Figure 7 clearly indicates that two pieces of the sensing fiber of the looped sensing fiber have different positions on the wedges, and one was closer to the core tooth than the other. Thus, two pieces of the sensing fiber experience different ventilation exposure, which may account for the 1.1˚C difference for these two pieces of the sensing fiber.

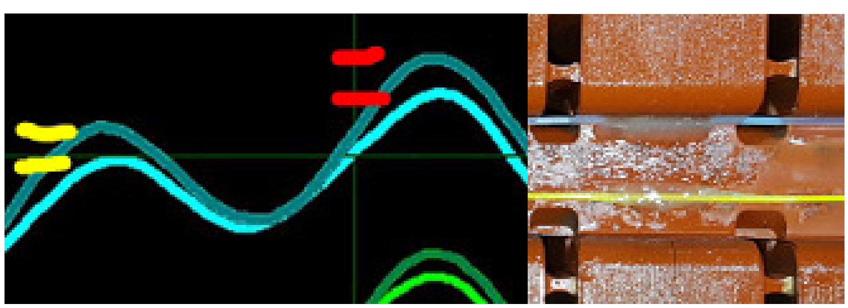

Fig. 7. Temperature difference because of sensing fibers for different ventilation exposure

3.2 Detection of 1cm hotspot

Tavner and Anderson [4] in their article on core failures state that "core faults usually, but not always, occur in the stator" and "core faults tend not to grow unless the initiating defect is >1 cm in diameter." The above results encourage us if we can detect a 1 cm hotspot using our DSTS. Since the spatial resolution of all current fiber optic distributed temperature sensors is not better than 10 cm, a 1 cm aluminum block, as shown in Figure 8, was used to verify that the DSTS has the capability to detect a 1 cm long hotspot. A certain length of fiber was coiled up before insertion into the block, and the remainder of 1 km fiber was spliced to the inserted fiber on the other side of the block, because 1 km optical sensing fiber is good enough to cover the whole stator of most gas generators. The fiber ran through a 1/16" PEEK plastic tube embedded in the block, so it was not in direct contact with the aluminum to approximate an actual generator installation configuration. Figure 9 displays the temperature measurements relative to a room temperature of 22.3°C when the temperature increased from 52.2°C to 100°C. The hotspot located around 204.40 m can be easily found when the temperature change is over 30°C (52.2°C – 22.3°C) within a 1 km length.

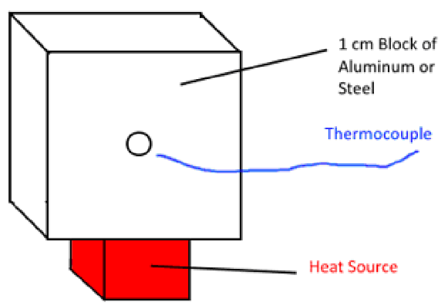

Fig. 8. Schematic of 1 cm hotspot

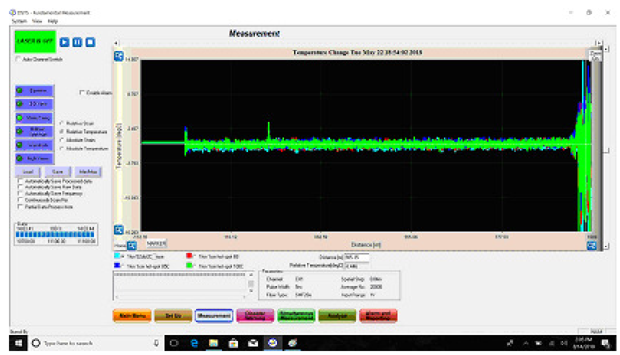

Fig. 9. 1 cm hotspot was detected within 1 km optical sensing fiber

3.3 GE oil + H_2-cooled generator

Note that the cooling system of this generator is different from the open air-cooled generator above. This generator utilizes pressurized H_2 contained within the generator frame as its cooling medium, and the physical dimensions of the unit and the layout of its ventilation flow are somewhat different designs. Despite size and layout differences, this generator utilizes a zone-cooled core and has a blower on each end just like the generator above, so we would expect to find a somewhat similar curve to the generator above, with corresponding wavy temperature deviations along the length of the sensor and a relatively cooler slot entrance/exit region. Figure 10 displays the temperature distributions along the sensing fiber, which was installed under the wedges in the base shim stock, falling well in line with expectations. The cursor denotes the loop-back point located at 273.91 meters. Curves are plotted for four different load points, ranging from 94.6 MVA to 154.0 MVA.

Unlike the first generator application where the fibers were almost directly influenced by ventilation flow due to the installation location, the fibers in this generator were largely removed from direct ventilation with the exception of the radial vents at the core. Additionally, the heating profile of the stator core is most intense in close proximity to the inner-diameter tips of the stator slots. These factors combine to predict that the measured temperatures would be higher than the embedded RTDs, which are both further away radially from the tips of the stator slots and circumferentially positioned away from the core iron on the order of 1 cm or more. This is what we have observed in the test data which is tabulated below, with temperature readings in centigrade.

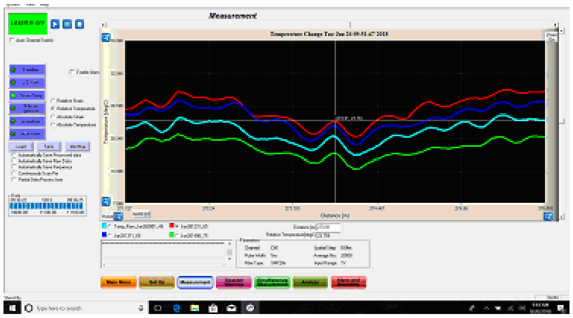

Fig. 10. Temperature distributions matched well against the existing RTD readings

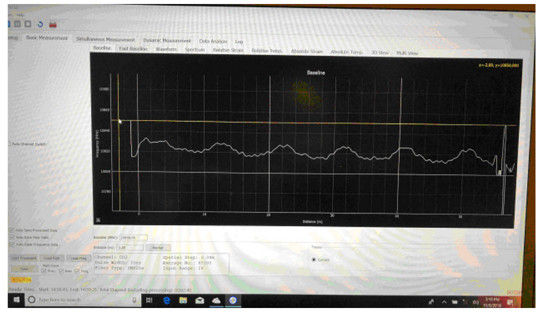

Fig. 11. Six peaks match 6 stator slots to be covered by optical sensing fiber

MW	MVAR	MVA	Cold Gas	Hot Gas	Embedded RTD	OZ DSTS
132.4	8.3	132.7	36.0	46.1	54.8	55.8
152.2	23.2	154.0	38.2	48.9	58.5	60.2
151.0	27.4	153.5	38.2	49.4	59.1	61.2
111.2	26.4	114.3	38.2	48.9	56.5	58.5
90.2	28.4	94.6	36.7	45.6	48.9	51.8

3.4 Hitachi oil + H_2-cooled generator

The sensing fiber was looped to cover six stator slots by using BOTDA. Unfortunately the sensing fiber was broken at the end of the last slot after the slots were covered by the wedges. Thus, we used a BOTDR for this application on the generator. Because the bottom of the generator was heated during the maintenance, the baseline illustrates 6 peaks that match 6 stator slots to be covered by optical sensing fiber.

3.5 Toshiba oil + H_2-cooled generator

Figure 12 displays the fiber optic temperature readings for 50 stator slots with optical sensing cable, with slot numbers listed in the approximate axial location. The red is max boost (45.1MW, +50.1VAR), green is near unity (45.4MW, +1.4MVAR), and blue is max buck (10MW, -36.2MVAR) condition. From Eqs. 1 and 2, DSTS can measure both temperature and strain. The readings for slots 57-66 are off a bit due to residual strain in the fiber, in which the stator experiences thermal expansion that creates a non-linear response to temperature changes. The selection and installation of optical sensing cable is very important to avoid strain affecting the temperature reading. All in all, the temperatures look to be essentially as expected, with the small exception of slots 69 and 6 showing readings about 4-5 degrees C warmer than expected during the max boost condition. That differential is interesting, but not at a level of concern.

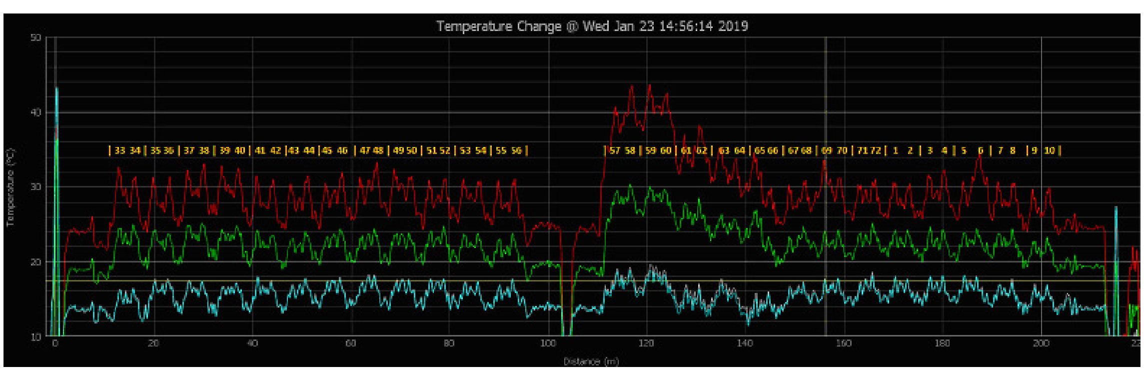

Fig. 12. Fiber optic temperature readings for 50 stator slots

Our DSTS has been beside this generator to keep monitoring the generator shown in Figure 13. More detailed results will be presented in the conference.

Fig. 13. DSTS keeps monitoring the generator

4. Conclusion

DSTS technology has proven to be an efficient and cost-effective solution to monitor temperatures in electrical generators. Furthermore, while the resolution is defined as 10 cm, DSTS technology can detect hot spots only 1 cm in length when the temperature changes over 30°C, opening the possibility for software solutions to define alarm and trip points to mitigate localized core damage which may occur during operation. The online temperature readings from the fiber optic line compared well against the existing RTD readings. More importantly, beautiful data curves emerged which clearly demonstrated the stator zone-cooling temperature affects along the length of the fiber installed in these generators.

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