Improving resilience and reliability of power grid: the role of fiber-optic distributed strain and temperature sensor for enhancing power system situational awareness

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SUMMARY

The electric power grid (EPG) is a dynamic system based on four main operations: generation, transportation, distribution and control. Failures can occur at any point on the grid, whether due to natural causes, operational errors, cyberattacks, or physical attacks. When any part of the EPG fails, it will have varying degrees of consequences on the entire power grid, leading to catastrophic events. Therefore, enhancing the situational awareness of EPG is crucial to prevent catastrophic events and improve the system's recovery capability (i.e., system resilience) after abnormal events.

Natural gas is an efficient and cleaner-burning energy source with fewer emissions than many other fossil fuels. It's also an important partner for renewables and emerging low-emission technologies. Modern combined cycle power plants, with state-of-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. Optical fiber ground wires (also known as OPGWs) are primarily used by the power grid industry and are placed in the secure topmost position of the transmission line where they "shield" all important conductors from lightning strikes while providing a telecommunications path for internal as well as third party communications, which improves communications, increases reliability, and enhances safety.

This paper presents the results of generator stator temperature profile tests that used a distributed strain and temperature sensing (DSTS) product, and were performed in a Siemens air-cooled generator and a GE H_2-cooled generator, owned by Calpine Corporation. Hot spots only 1 cm in length can be detected by DSTS technology when the temperature changes 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. A potential real-time monitoring application using OPGW is presented also. OPGW cables, by the nature of their aerial installation, are subject to wind, ice buildup and temperature fluctuations. The ability to monitor the strain experienced by individual fibers (helically wound inside) over the entire length of the cable (67 km) and measure strain at short (10 m) intervals is valuable, which can provide enhanced capability to measure the dynamic response of OPGW fibers to environmental elements such as wind, temperature and ice. DSTS technology has proven to be an efficient and cost-effective solution to improve resilience and reliability of power grid by enhancing power system situational awareness.

KEYWORDS

Electric power grid, Modern combined cycle power plants, Gas turbines and steam turbines, Air-cooled and H_2-cooled electrical generators, Eddy currents, Core damage of electrical generators, Fiber-optic sensor, Distributed strain and temperature sensor (DSTS), Brillouin scattering, Optical fiber ground wire (OPGW)

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1. Introduction

Modern combined cycle power plants, with state-of-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 requires 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. Optical fiber ground wires (OPGWs) are primarily used by the power grid industry and are placed in the secure topmost position of the transmission line where they "shield" all important conductors from lightning strikes while providing a telecommunications path for internal as well as third party communications, which improves communications, increases reliability, and enhances safety.

Brillouin scattering based distributed strain and temperature sensing (DSTS) [1] provides an excellent opportunity for power generator applications, because it is unaffected by electromagnetic interference (EMI) and vibration. OPGW cables, by the nature of their aerial installation, are subject to wind, ice buildup and temperature fluctuations. The ability to monitor the strain (absolute or relative) experienced by individual fibers (helically wound inside) over the entire length of the cable (67 km) and measure strain at short (10 m) intervals is valuable.

In this work we report our DSTS products based on coherent interaction of probe and pump have been successfully employed to monitor temperature profile of an air-cooled gas generator by measuring the temperature distributions along the surface of the stator of the air-cooled gas generator with 10cm spatial resolution, to predict mechanical failure of fiber optic cables by measuring strain distributions along the cables, and to identify the effects of thunderstorms and rime ice on an Optical Ground Wire (OPGW) cable by monitoring strain on 134km OPGW fibers.

2. Temperature profile monitoring of an air-cooled gas generator and a H_2-cooled generator with 10cm spatial resolution

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 (shown in Figure 1) in Hermiston, OR, USA and a GE H_2-cooled generator (shown in Figure 2 that

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displays the sensing fiber installed under the wedges in the base shim stock) in Hidalgo, TX, USA operated by Calpine Corporation, respectively.

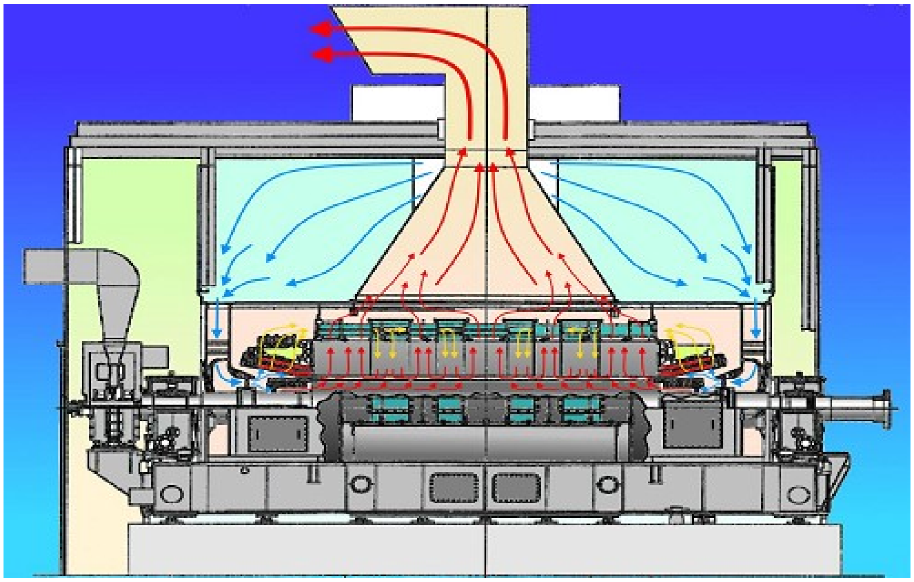

Fig. 1 Machine configuration of Siemens Westinghouse–AeroPac I–open air cooled generator showing with radically vented, zone-cooled core.

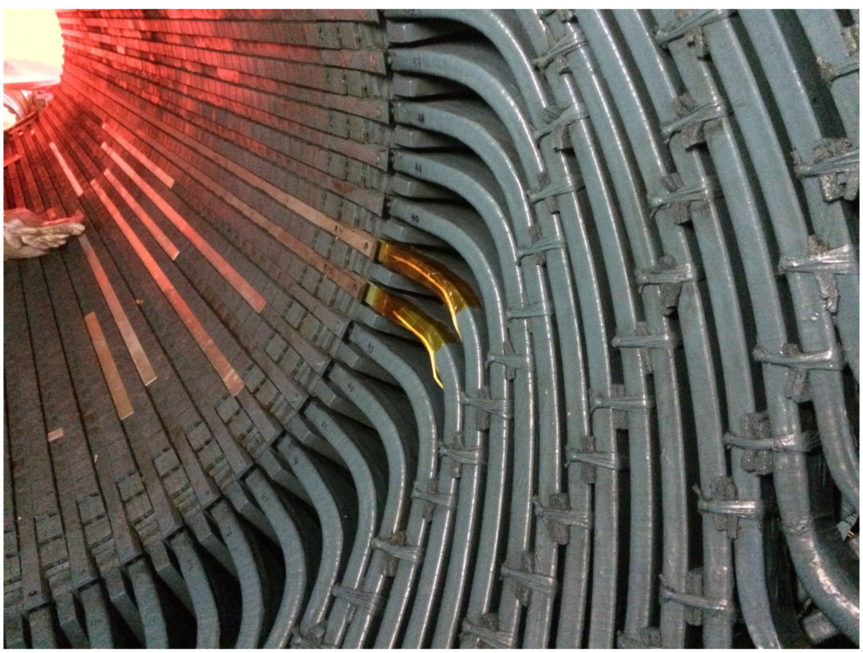

Fig. 2. GE H_2-Cooled generator

2.1 Siemens open air cooled generator

Figure 3 displays temperature distributions along the sensing fiber installed on top of the stator wedges when the power loading increased from 25MVA to 170MVA, which demonstrated the

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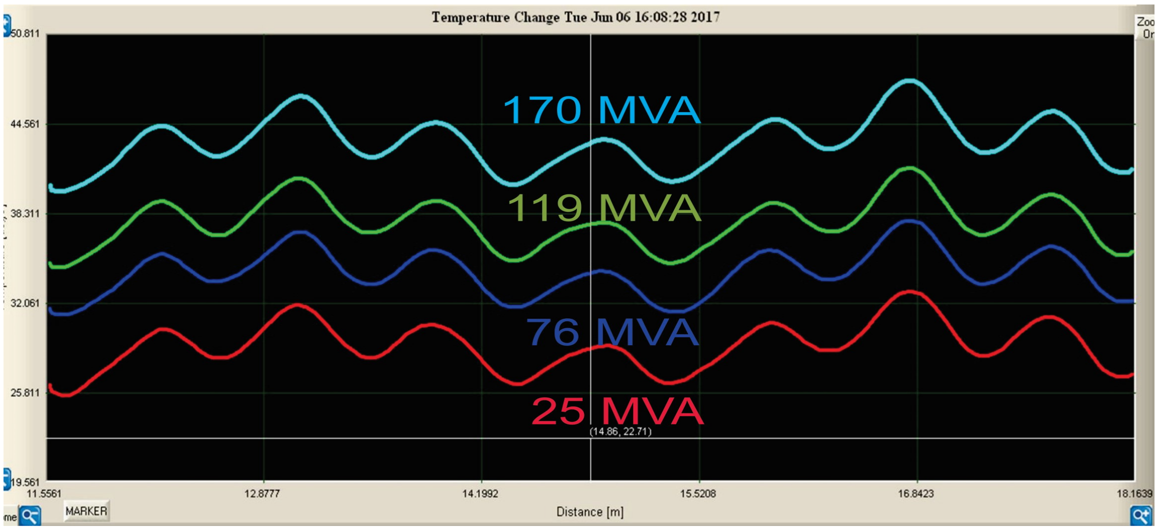
stator zone-cooling temperature affects along the length of the fiber and shows the temperature increasing with the loading of the generator and the temperature profiles with peaks and valleys matching the radially vented, zone-cooled core of the generator shown in Fig. 4 in which the light color lines are the images of the left parts of the cursor located at the loop back point of the sensing fibers shown in Fig. 3.



Fig, 3 Distributions of temperatures along the sensing fiber set-up measured with 1ns pulse duration. The cursor is corresponding to the loop back point of the sensing fibers.

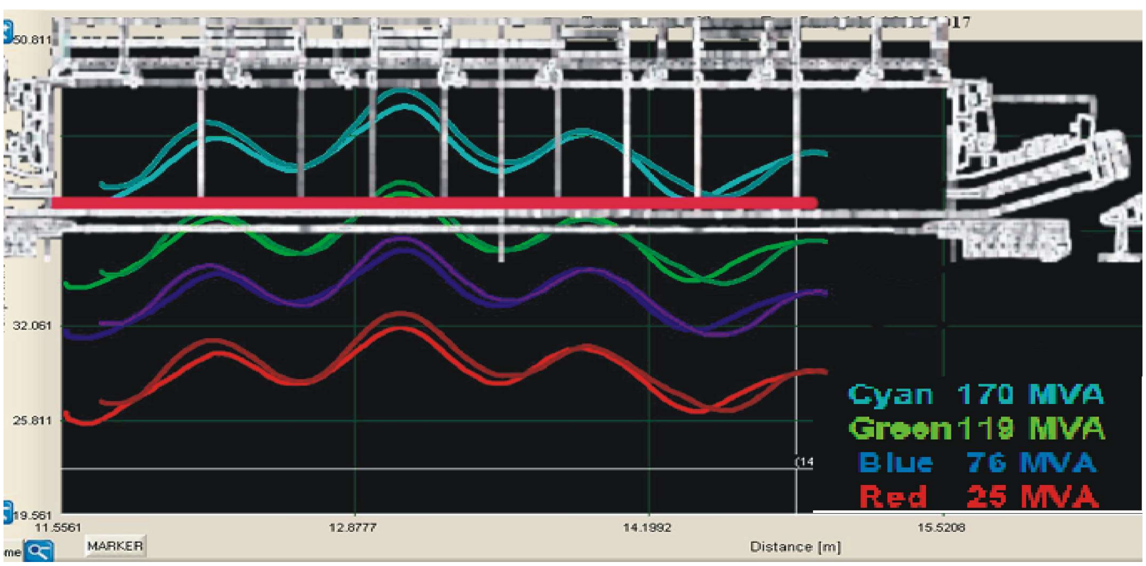


Fig. 4 Temperature profiles with peaks and valleys matching the radially vented, zone-cooled core of the generator. The light color lines are the images of the left parts of the cursor located at the loop back point of the sensing fibers shown in Fig. 3.

2.2 GE H_2-cooled generator

P.J. Tavner and A.F. Anderson [2] 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

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is >1 cm in diameter." 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 5, 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 into the inserted fiber on the other side of the block. 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 6 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 204.40m can be easily found when the temperature change is over 30°C (52.2°C – 22.3°C) within a 1 km length.

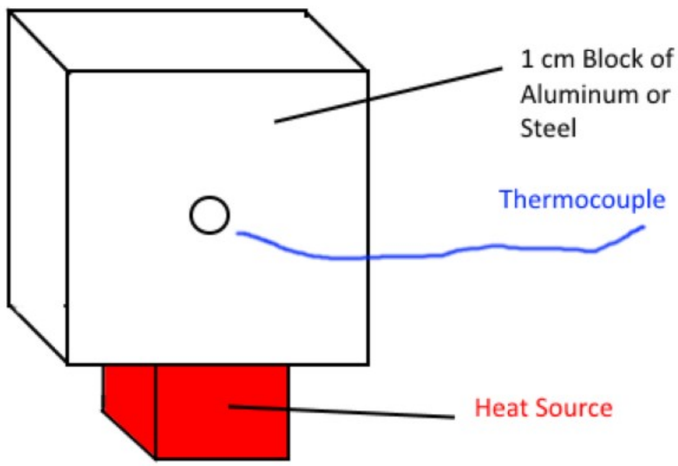

Fig. 5. Schematic of 1 cm hotspot.

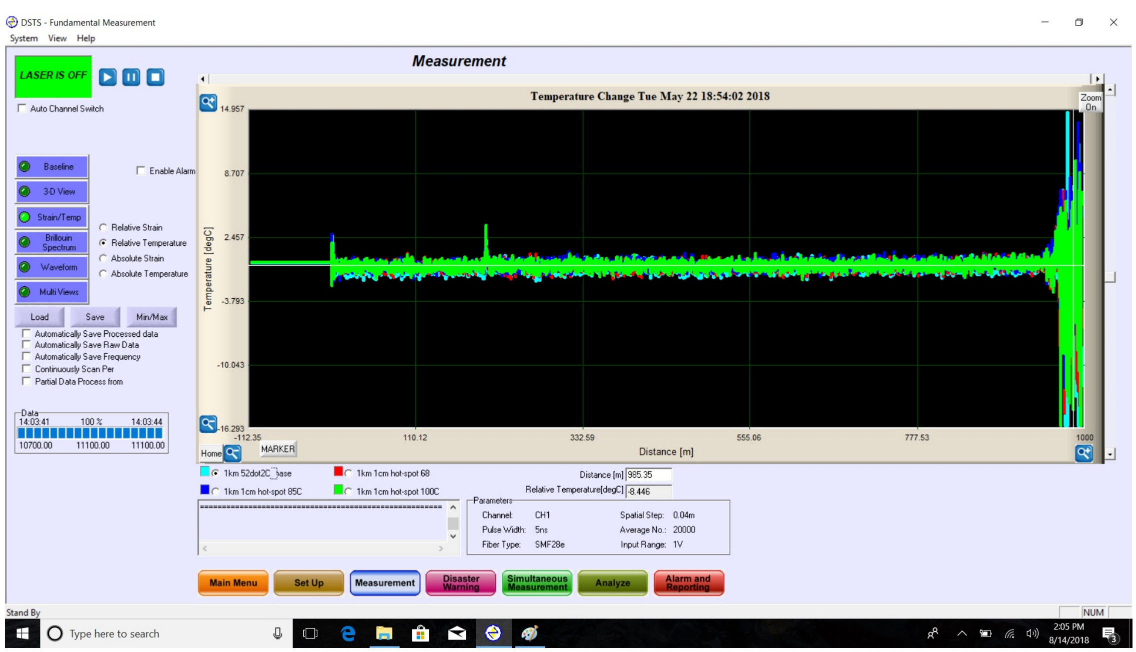

Fig. 6. Within a 1 km fiber a 1 cm hotspot was measured

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Note that the cooling system of this generator is different from the 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 7 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.

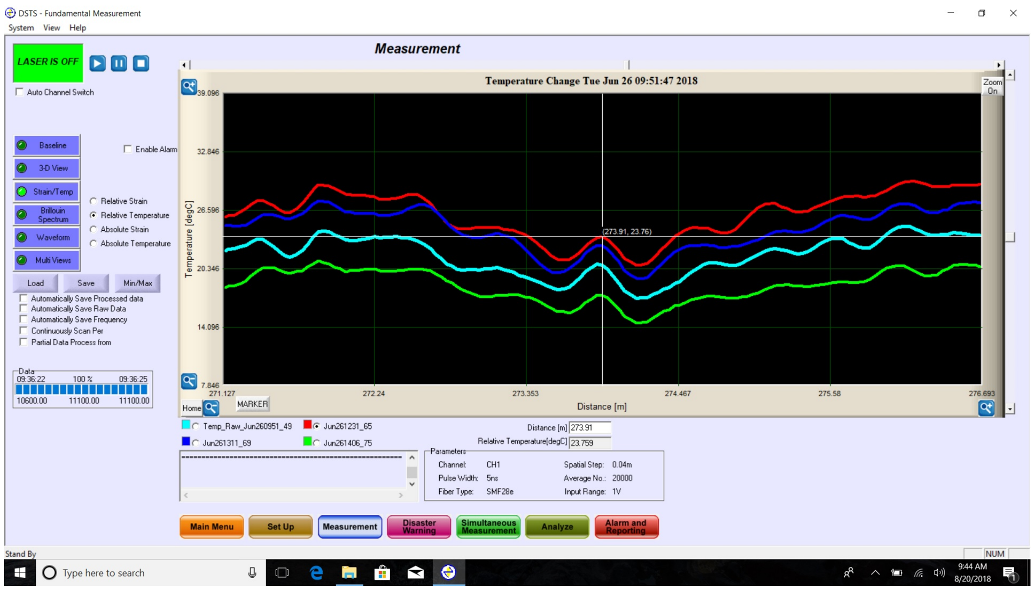


Fig. 7. Temperature distributions matched well against the existing RTD readings.

Unlike the first generator 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.

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

In summary, it is cleanly shown that the temperature profile matches the designed Siemens air-cooling profile and the temperatures on the stators in the Siemens air-cooled generator and the GE H_2-cooled generator increase with loading that matches embedded RTDs temperature measuring from the control room.

3. Long-term monitoring of local stress changes in 67-km installed OPGW Cable with 134-km fibers

Optical Ground Wire (OPGW) has been used in place of shield wire (or ground wire which is the highest conductor on the tower) on high voltage transmission lines since the early 1980’s. The wide bandwidth and immunity from electromagnetic induction makes optical fibers (inside OPGW) an attractive choice for utility telecommunication needs. Availability of existing right-of-way makes installation of OPGW cost-effective. With some exceptions, almost all OPGW cables are grounded at every tower. The basic function of the cable is to provide lightning protection for the transmission line as well as to help dissipate fault currents that may be experienced by the components of the power system. The fiber optic strands inside OPGW are used for both power system protection and for commercial applications where bandwidth or dark fiber capacity is sold to commercial telecom operators.

The OPGW cable is installed in the Eastern Ontario, Canada. The cable distance between two stations (Station “A” in Ottawa and the other referred to here as Station “B”) is 67 km, as shown in Figure 8. Starting from Station “A” (Ottawa area), the cable composition consists of a station cable fiber of approximately 1 km of Corning SMF-28 non-dispersion shifted fiber (NDSF) inside a dielectric jacket cable. The fibers are spliced to ITU G.652 (similar to Corning SMF-28 NDSF) fibers inside the central aluminum core of an OPGW cable. This is followed by 51 km of ITU G.653 dispersion-shifted fiber (DSF), also inside the central aluminum core of the OPGW. Finally, the route terminates in another 0.5 km of station cable at Station “B”, consisting of Corning SMF-28 NDSF inside dielectric jacket cable. It should be noted that not only the fiber types (ITU G.652 vs. G.653) are different for the 51 km and the 14 km segments, but also the construction/composition of the OPGW cables are different.

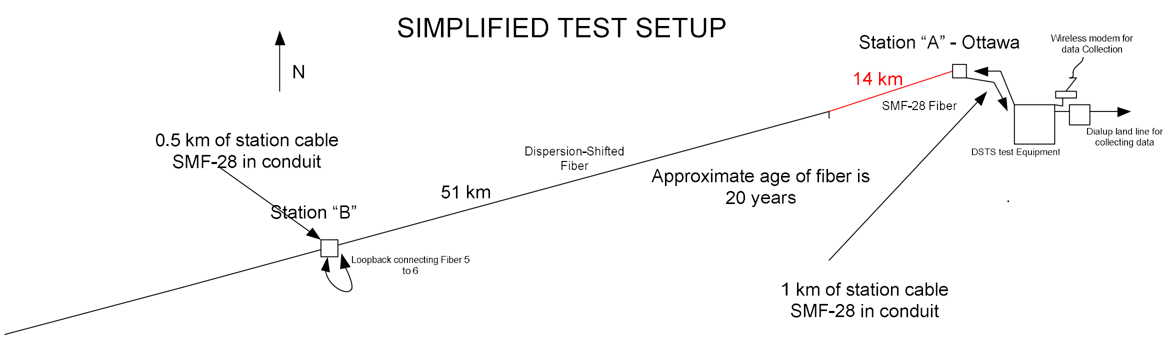


Fig. 8 Experimental set-up.

The BOTDA test equipment requires access at both ends of the fiber, so loop back was used at Station “B”. Thus, the total fiber length monitored by the Brillouin sensor is 134m. The BOTDA, located at Station “A” in Ottawa, was set to scan as often as once every 60 minutes, starting on June 12, 2012 and continuing to June 17, 2013. Much data was collected as part of this experiment. The data points correspond to running averages of strain experienced by the fiber at 10 m intervals along the 67 km length of OPGW.

A wireless modem was installed with the DSTS test equipment to send warning messages to the project manager when strain changes reached specified criteria. A dialup landline was used to transfer data from the DSTS test equipment to the main office. A sketch of the test setup is shown in Figure 8.

Figure 9 displays the Brillouin frequency shifts over the length of the fiber. The loop back point is located at 66.6-km, where station “B” is located. The loop back distance corresponds exactly to the DSTS measured length. The analysis need only focus on the first 66.6-km to get strain distribution, and ignore the results after that.

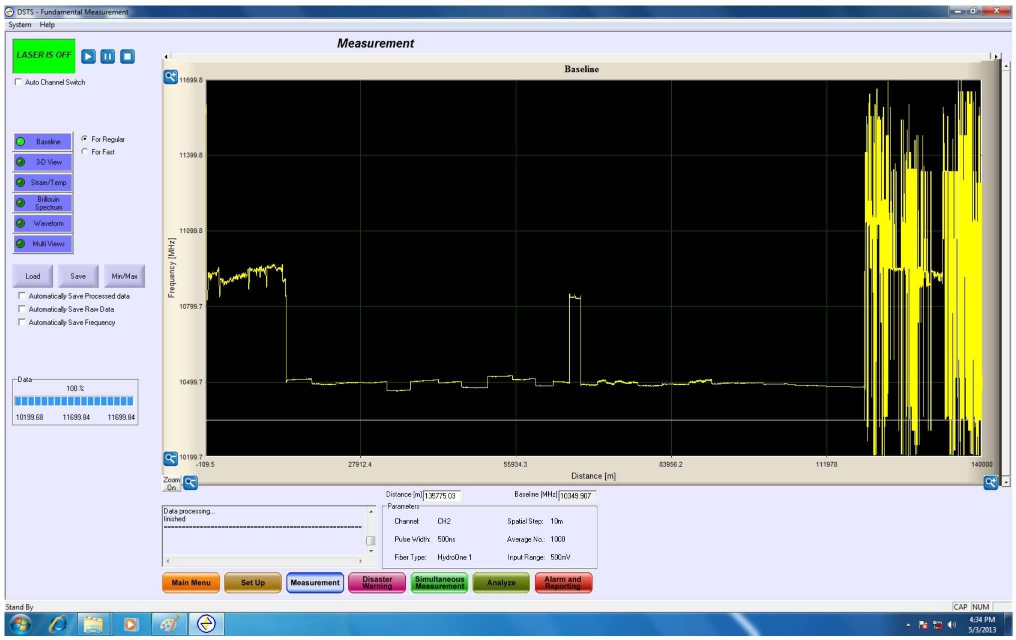
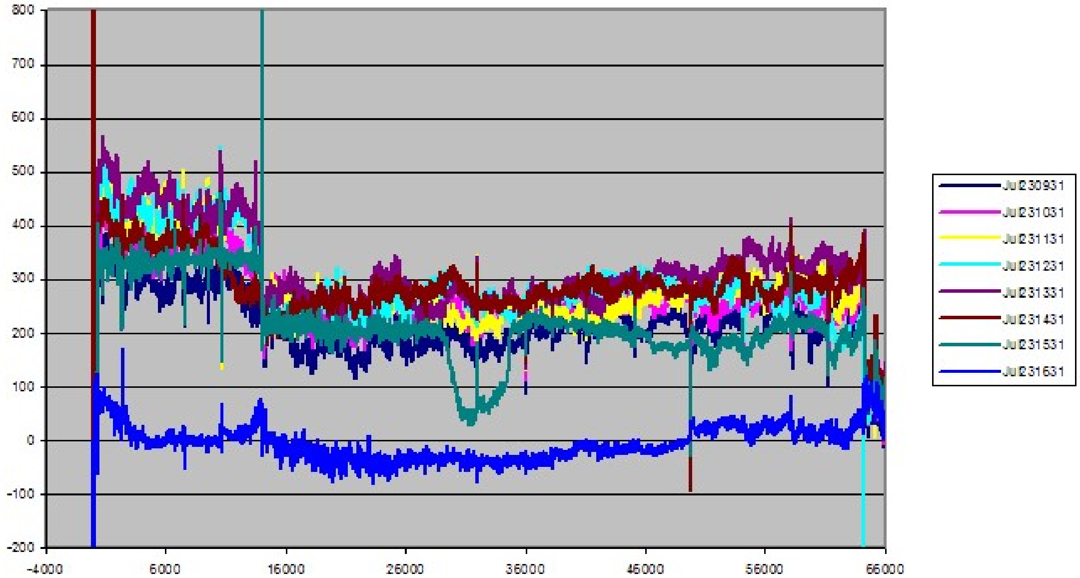


Fig. 9 Brillouin frequency shifts along the fiber, loop back point located at 66.6-km (the high reflectance event).

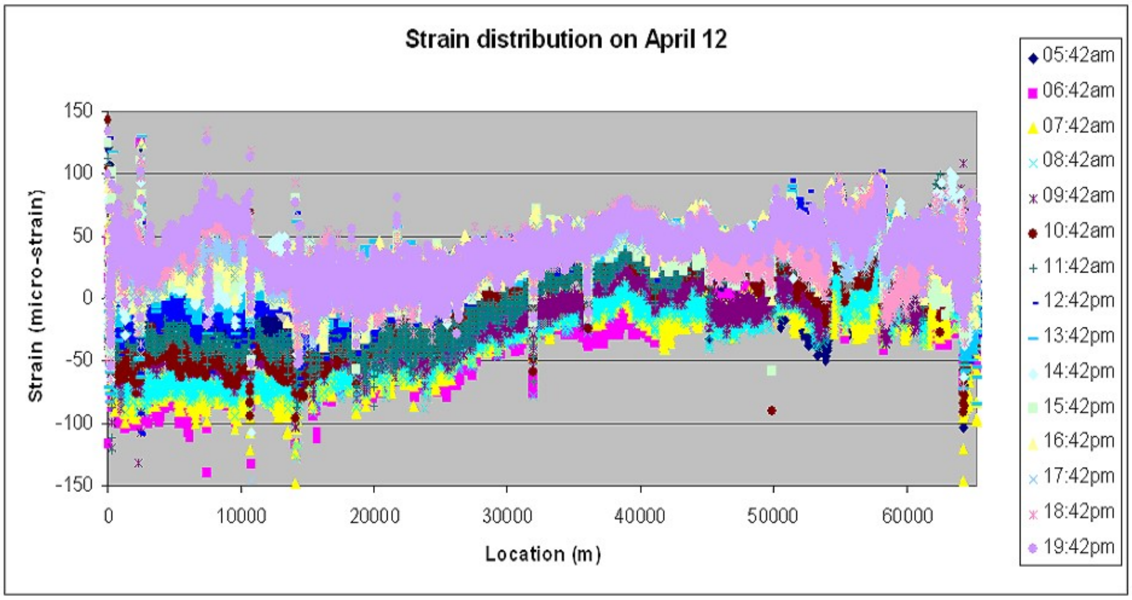
At 15:31 PM (EDT) July 23, 2012, a sudden drop in strain was observed approx. 28-34 km away from the Ottawa test start location. Shock cooling of OPGW cable due to thunderstorm rain could be the cause. Temperature compensated data are shown in Figure 10.

Further investigation of weather at the Ottawa International Airport (CYOW) that is around 5 km away from the Station “A” in Ottawa where the BOTDA located for this test - compiled from Weather underground (www.weatherundeground.com) shows that a severe thunderstorm with associated rain and gusting wind was present in this area at that exact same time. Furthermore, a large change in wind direction was noted at about the same time. It appears that the correlation between thunderstorm effects (due to cold front crossing) matches the event shown on the DSTS graph on July 23, 2012 @ 15:31. The lower strain experienced following the event and measured at 16:31 PM corresponds to the cooling of the air (and the cable) due to a cold front. A temperature drops from 30°C to 22-21°C is noted in weather details. The use of BOTDA DSTS provided a window on the effect of a thunderstorm on the cable. The hypothesis is that a large (approx. 6 km) thunderstorm front crossed the transmission line at this time, affecting the OPGW cable and the fiber strands inside the OPGW. It is possible that cooling of the OPGW strands due to cold rain from the thunderstorm (as it passed through a segment of the line) contracted the cable, reducing its sag that reduced strain on the fiber by almost 150με. This could lead to interesting applications for monitoring of sag (and tension) on cables. Other applications in the metrology may also be possible.

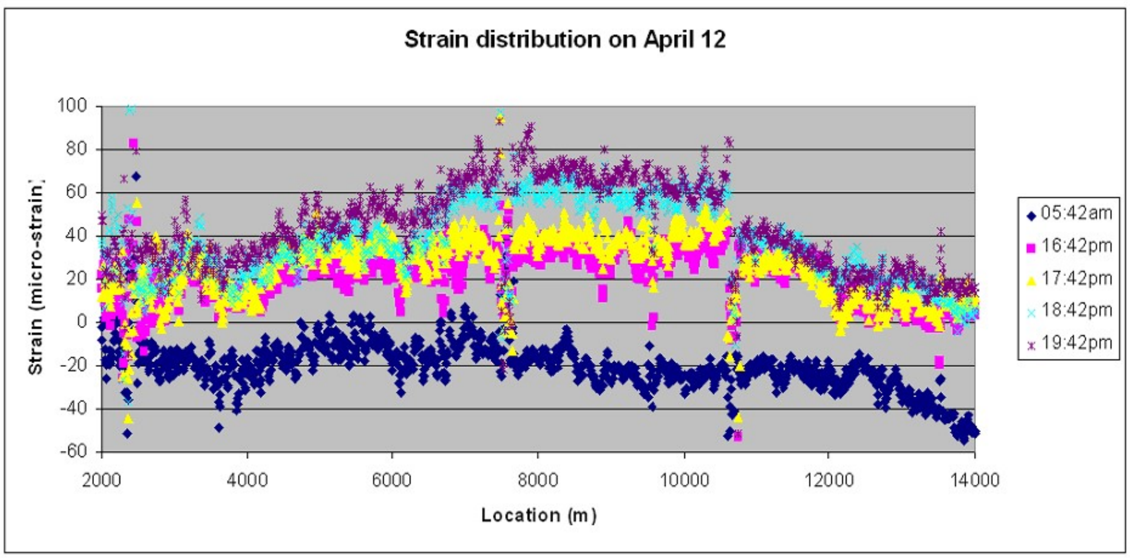


Fig, 10 Strain measurements prior, during, and after the thunderstorm in the Eastern Ontario region.

On April 12, 2013, a snowstorm occurred in the Ottawa area in the early-morning hours and continued through the day with a mix of ice pellets, freezing rain, snow and rain. While April snow flurries happen from time to time in the Ottawa area, the characteristics of this storm, with temperatures and dew points hovering around 0°C, resulted in icy conditions which paralyzed the region quickly. According to the weather report, the temperature stayed close to 0°C. Figure 11 shows the effect of the snowstorm on the first 7-km of fiber cable West of Ottawa, Ont. The measurement closest to 05:00 AM can be used as a baseline. These measurements clearly show that strain increases with time from 05:42 to 19:42 which can be correlated with possible ice accumulation on the OPGW cable. The strain increase on the NDSF fiber (first 14 km) is shown in Figure 12. The maximum strain change (relative strain) on the fibers inside the OPGW (on the first 14 km) is around 60με, (from -20με to +40με). A word of caution is that the exact strain values here should not be dwelled upon in these results and the trend in the results is what is deemed important. All strain measurements are relative to the June 12, 2012 reference level, hence negative numbers are possible. A probable cause for increased tension due to this event is possible that the temperature/dew point hover close to 0°C in presence of precipitation, producing rime ice that accumulated on the cable. This is similar to the ice that forms on the leading edge of on aircraft wing. Any cable that gets coated with ice becomes heavier, stretching, resulting in higher sag (and tension) and thus higher strain on the actual fibers inside.



Fig, 11 Strain Measurements on the fiber corresponding to the Ottawa area on April 12, 2013.



Fig, 12 Strain distribution on April 12 on the first 14 km Fiber.

In summary, the effects of weather phenomena such as thunderstorm and snowstorm (with potential ice build-up) on aerial cable (e.g. OPGW in this case) can be identified by monitoring relative strain on the OPGW. Variations of strain on the fiber during the warm days and going from day to nighttime can be observed with the DSTS. Combined with fiber temperature data from BOTDA, some useful information on cable surface temperature can be extrapolated.

4. Conclusions

The DSTS products have been successfully employed to monitor temperature profile of a Siemens air-cooled generator and a GE H_2-cooled generator by measuring the temperature distributions along the surface of the stator with 10cm spatial resolution. Hot spots only 1 cm in length can be detected by DSTS technology when the temperature changes over 30℃. 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. A potential real-time monitoring application using OPGW is presented also. OPGW cables, by the nature of their aerial installation, are subject to wind, ice buildup and temperature fluctuations. The ability to monitor the strain experienced by individual fibers (helically wound inside) over the entire length of the cable (67 km) and measure strain at short (10 m) intervals is valuable, which can provide enhanced capability to measure the dynamic response of OPGW fibers to environmental elements such as wind, temperature and ice. DSTS technology has proven to be an efficient and cost-effective solution to improve resilience and reliability of power grid by enhancing power system situational awareness.

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