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Fiber-Optic Distributed Strain and Temperature Sensor for Enhancing Power Grid Reliability and Utilization

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SUMMARY

Over the last several decades, electricity consumption and generation have continually grown. Investment in the Transmission and Distribution (T&D) infrastructure has been minimal and it has become increasingly difficult and expensive to permit and build new power lines. At the same time, a growing increase in the penetration of renewable energy resources is causing an unprecedented level of dynamics on the grid. Consequently, the power grid is congested and under stress. The task of monitoring asset status and optimizing asset utilization for the electric power industry seems particularly challenging. The lack of situational awareness compromises system reliability, and raises the possibility of power outages and even cascading blackouts.

Fiber-optic sensing technology is best adapted to health monitoring and evaluation of power grids because of its immunity of electromagnetic interference, capabilities of multiplexing and distributed sensing, and tolerance to harsh environments. One of Fiber-optic sensing technologies is Brillouin scattering based distributed strain and temperature sensing (DSTS) using optical fiber transmission media as a sensor to remotely measure both strain and temperature at any location on the optical fiber. On the other hand, optical fiber composite overhead ground wire (OPGW) is used extensively as power transmission lines, which prove the priority of the fiber-optic sensing technology naturally. The losses caused by natural disasters (e.g., rainstorm, snowstorm, and thunder striking) to the power grid are enormous. Overhead transmission lines are easily suffered from the impact of complex meteorological and geographical conditions. Galloping, windy, icing, and temperature of transmission lines are the main objects of observation. The abnormity of temperature is one of early signs for the potential failure of transformers, and power generators as well. Power towers are threatened by landslides, debris flows, erections of foundation settlement, lines galloping, and so on, which induce considerable strain, tilt, and deformation of the power towers.

In this paper, we report that we have been using DSTS to form an intelligent fault diagnosis system for the health monitoring and evaluation of a power grid in real time, which includes one calendar year of monitoring a 67 km length of OPGW cable strung on high voltage power lines, achievement of high accurate temperature monitoring during H_2-cooled generator operation with seal oil system, and detection of deformation of steel structure by measuring the longitudinal strain distributions along the surface of the steel structure. The results show that 1) additional strain can be measured during significant meteorological events such as a thunderstorm or snowstorm and the effect of rime ice buildup on the OPGW cable can be also noticed; 2) hot spots only 1 cm in length for H_2-cooled generator with seal oil system can be detected when the temperature changes over 30°C and temperature profiles can clearly demonstrate that the stator zone-cooling temperature affects along the length of the fiber installed in these generators; 3) the locations of localized deformation of steel structure can be found and distinguished using their corresponding strain-load data.

KEYWORDS

Power grid reliability and utilization, Fiber optic distributed sensor, OPGW, Localized deformation of steel structure, Seal oil system

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1. Introduction

Over the last several decades, electricity consumption and generation have continually grown. Investment in the Transmission and Distribution (T&D) infrastructure has been minimal and it has become increasingly difficult and expensive to permit and build new power lines. At the same time, a growing increase in the penetration of renewable energy resources is causing an unprecedented level of dynamics on the grid. Consequently, the power grid is congested and under stress. The task of monitoring asset status and optimizing asset utilization for the electric power industry seems particularly challenging. The lack of situational awareness compromises system reliability, and raises the possibility of power outages and even cascading blackouts.

Fiber-optic sensing technology is best adapted to health monitoring and evaluation of power grids because of its immunity of electromagnetic interference, capabilities of multiplexing and distributed sensing, and tolerance to harsh environments. One of Fiber-optic sensing technologies is Brillouin scattering based distributed strain and temperature sensing (DSTS) using optical fiber transmission media as a sensor to remotely measure either temperature or strain or both temperature and strain at any location on the optical fiber through

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

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

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, Zou *et al.* [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.

On the other hand, optical fiber composite overhead ground wire (OPGW) is used extensively as power transmission lines, which prove the priority of the fiber-optic sensing technology naturally. The losses caused by natural disasters (e.g., rainstorm, snowstorm, and thunder striking) to the power grid are enormous. Overhead transmission lines are easily suffered from the impact of complex meteorological and geographical conditions. Galloping, windy, icing, and temperature of transmission lines are the main objects of observation. The abnormity of temperature is one of early signs for the potential failure of transformers, and power generators as well. Power towers are threatened by landslides, debris flows, erections of foundation settlement, lines galloping, and so on, which induce considerable strain, tilt, and deformation of the power towers.

In this paper, we report that we have been using DSTS to form an intelligent fault diagnosis system for the health monitoring and evaluation of a power grid in real time, which includes one calendar year of monitoring a 67 km length of OPGW cable strung on high voltage power lines, achievement of high accurate temperature monitoring during H_2-cooled generator operation with seal oil system, and detection of deformation of steel structure by measuring the longitudinal strain distributions along the surface of the steel structure. The results show that 1) additional strain can be measured during significant meteorological events such as a thunderstorm or snowstorm and the effect of rime ice buildup on the OPGW cable can be also noticed; 2) hot spots only 1 cm in length for H_2-

cooled generator with seal oil system can be detected when the temperature changes over 30°C and temperature profiles can clearly demonstrate that the stator zone-cooling temperature affects along the length of the fiber installed in these generators; 3) the locations of localized deformation of steel structure can be found and distinguished using their corresponding strain-load data.

2. Experimental Setup

2.1 Temperature and strain measurements on Optical Ground Wire (OPGW)

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. The OPGW cable for this test 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 1. 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. In this test, to enhance high spatial resolution and high temperature and strain resolution we used BOTDA feature of DSTS that requires access at both ends of the fiber, so loopbacks were used at Station "B". Thus, the total fiber length monitored by DSTS is close to 140 km. 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 sketch of the test setup is shown in Figure 1.

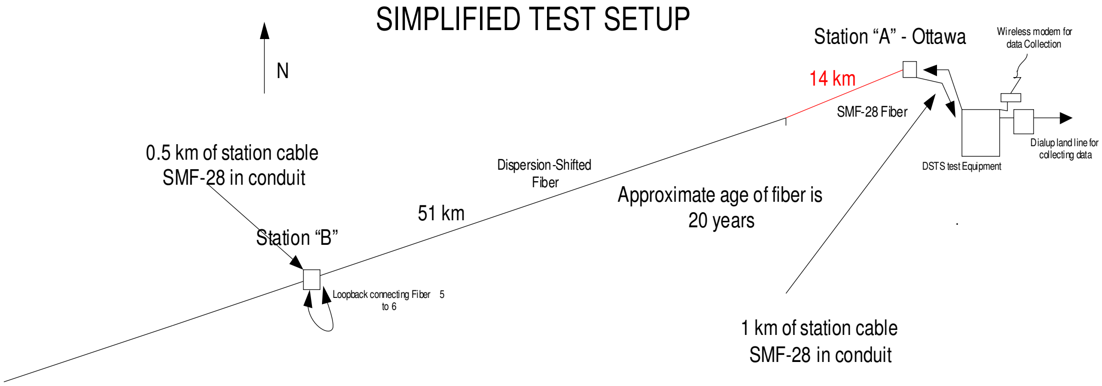


Figure 1. Experimental setup for temperature and strain measurements on OPGW

2.2 Optical sensing cable installation for H_2-cooled generator with seal oil system

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 tubing can be placed in direct contact with the stator laminations, stator coil groundwall, or both simultaneously. The DSTS application for a power generator with this kind of optical sensing cable was installed into Calpine's Hidalgo CTG1 GE H_2-cooled generator with seal oil system as shown in Figure 2 that displays the sensing cable installed under the wedges in the base shim stock to cover two stator slots and optical sensing cable installed outside the generator for connecting to DSTS system.

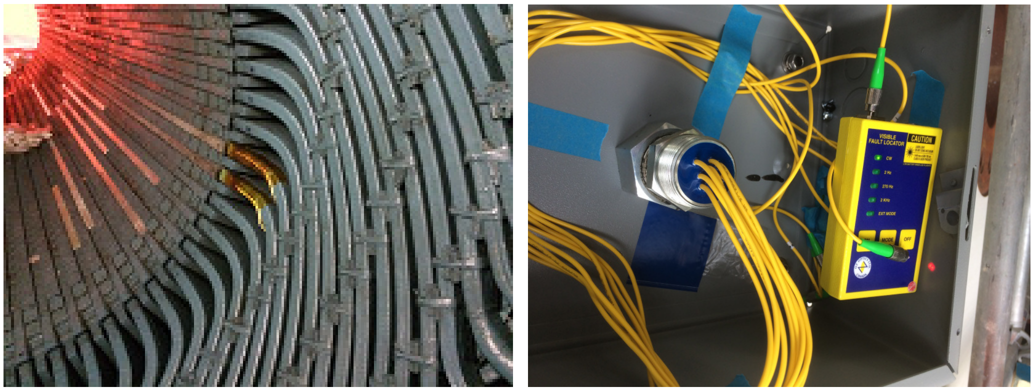


Figure 2. Optical sensing cable installed in GE H_2-cooled generator with seal oil system

2.3 Optical sensing cable installation for detecting deformation of steel structure

The power tower is mainly used to erect high-voltage wires and lines. It is an important infrastructure for overhead transmission lines and an electric bridge. It plays a role in supporting wires, insulators and related power facilities, and can keep them adequate for the earth and other buildings safe distance. Therefore, the operation of the tower will directly affect the safe operation of the transmission line, which is related to the safety and benefits of the entire power grid system. In this test, we used steel pipe to simulate deformation monitoring of power tower through DSTS. To prepare the steel structure for fiber installation, sandpaper was used to remove irregularities and provide a smooth, uniform surface around its circumference. An acrylate buffered SMF-28 optical fiber was used for monitoring both the environmental temperature conditions and the strain distributions along the pipe. Ten sensing sections were mounted externally on the pipe to monitor the strain changes on the outer surface and protected by a special design adhesive, as shown in Figure 3. Each 2 m sensing fiber symmetrically located in the central portion of the steel pipe with 1 m loose fibre separating one sensing section from another. The longitudinal strain distribution along the steel structure can be measured from each sensing section and hoop strain distribution around the circumference of the pipe at any locations of the steel structure can be obtained from these ten sensing sections. The environment temperature was kept constant during strain measurements.

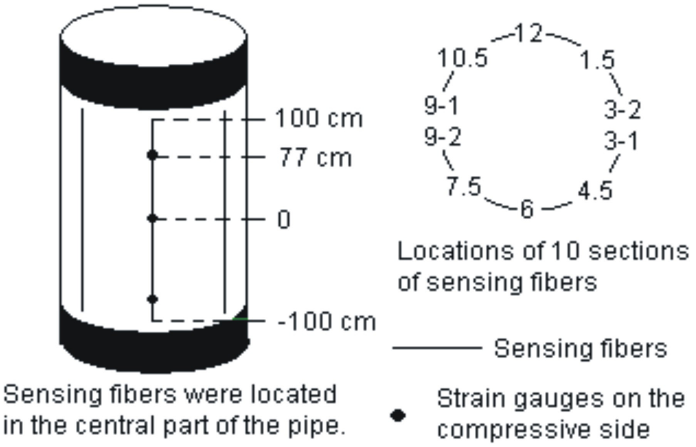


Figure 3. Schematic diagram of optical sensing fibers installed in a steel pipe

3. Results and discussion

3.1 Analysis of Weather Phenomena experienced by OPGW

On July 23, 2012, at 15:31 PM EDT (Ottawa), 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, but it is just a speculation. It needs to have further investigation. Temperature compensated data are shown in Figure 4**.**

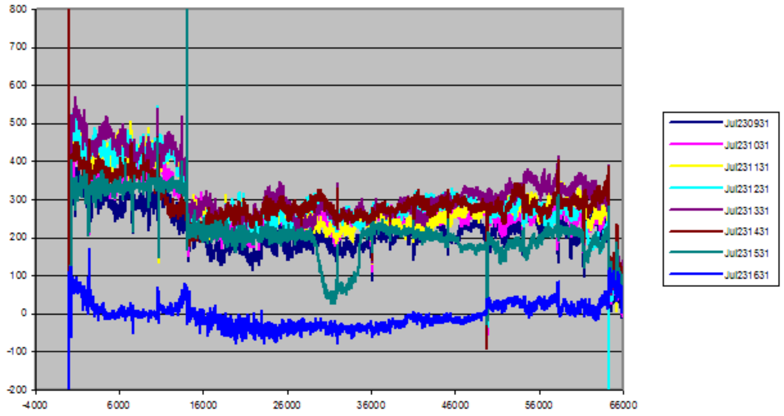


Figure 4. Strain measurements prior, during and after the thunderstorm in the Eastern Ontario region

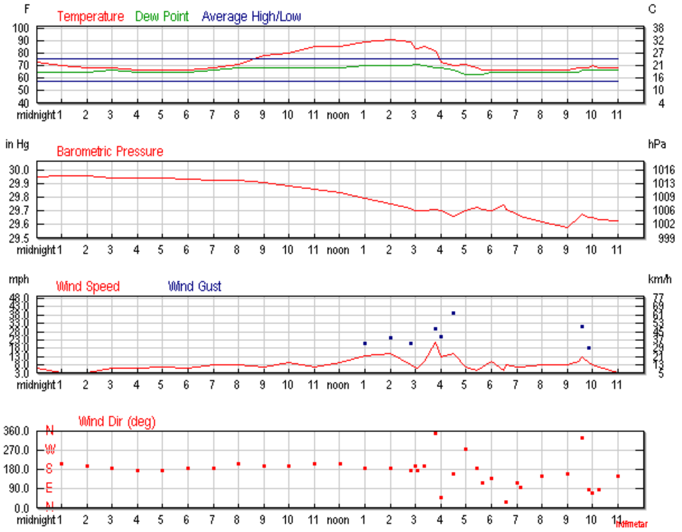


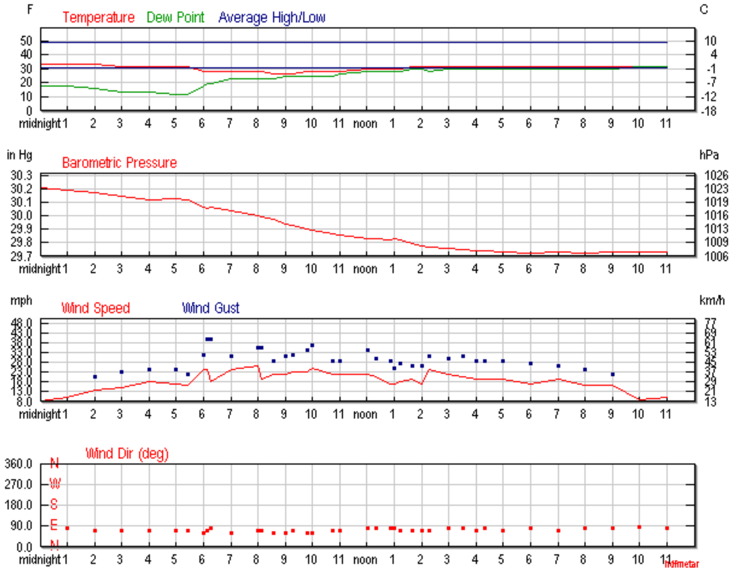
Figure 5. Temperature/Humidity/Wind at Ottawa, Ontario, on July 23, 2012 (Source: weatherunderground [4])

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 as shown in data (Figure 5). 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 which reduced strain on the fiber by almost 150 $\mu\varepsilon$. If validated, this could lead to interesting applications for monitoring of sag (and tension) on cables. Other applications in the metrology may also be possible. The validation, however, requires further research in a controlled laboratory environment.

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.

Weather reports and hourly data for this event are provided as (Source: weatherunderground [4]) :



According to the weather report, the temperature stayed close to 0°C. 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 effect of snow/ice storm passing through the region (first 14 km NDSF fiber) is seen on the DSTS strain data shown in Figure 6. The maximum strain change (relative strain) on the fibers inside the OPGW (on the first 14 km) is around 60 με, (from -20 με to +40 με). 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 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.

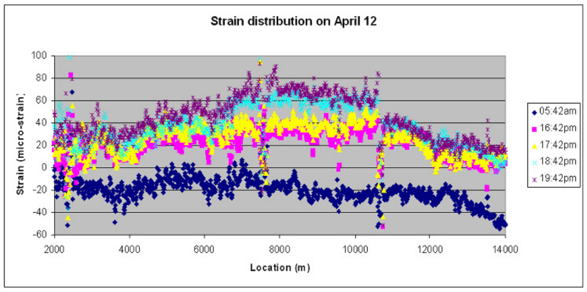
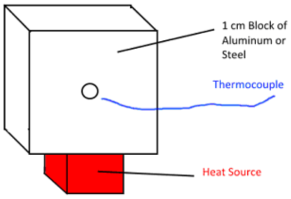


Figure 6. Strain distribution on April 12 on the first 14 km Fiber

3.2 Detection of 1cm hotspot and GE oil + H_2-cooled generator

Tavner and Anderson [5] 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.” 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 7, 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 8 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 sensing length.



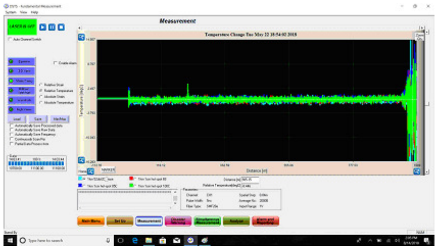


Figure 7. Schematic of 1 cm hotspot **Figure 8. 1 cm hotspot was detected within 1 km optical sensing fiber**

The generator utilizes a zone-cooled core with pressurized H_2 contained within the generator frame as its cooling medium and has a blower on each end, so we would expect to find a temperature curve with corresponding wavy temperature deviations along the length of the sensor and a relatively cooler slot entrance/exit region. Figure 9 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. 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.

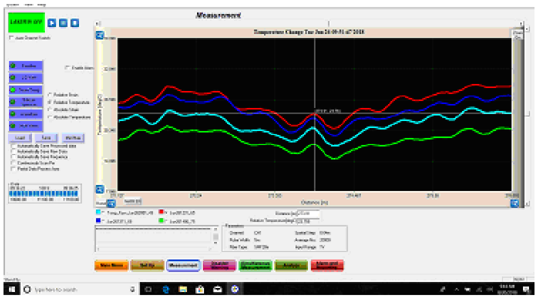


Figure 9. Temperature distributions matched well against the existing RTD readings

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

3.3 Detection of deformation of steel structure

The tested steel pipe was sealed on both ends and filled with water by keeping internal pressure of 18.4 MPa (2669 psi) during pipe deformation test. The concentric and bending loads were employed by a Universal Test System (UTS). The concentric load was used to balance internal pressure. The strain measurements were taken at every 334 kN (75 kips) when the bending load was changed from 0 until the localized pipe-wall deformation occurred. Longitudinal directions of 6 and 12 o'clock along the steel pipe were subjected to tension and compression, respectively. Strain gauges were distributed longitudinally along directions of 6 o'clock (tensile side) and both 3 and 9 o'clock (neutral lines). Three strain gauges were installed longitudinally along the steel pipe on the compressive side, as shown in Figure 3. The external profiles of the steel pipe on the compressive side were also monitored by a laser scanner.

The strain distributions along 12 o'clock section of the steel pipe on the bending load of 979 kN (220 kips) and 1,335 kN (300 kips) are presented in Figure 10. Obviously this section experienced more compression compared to that on zero bending load. It shows clearly that our sensor system can offer continually distributed information of strain along the steel pipe. When the middle point of the steel pipe is chosen as the original of an axis, for the bending load of 979 kN (220 kips) and 1,335 kN (300 kips), the maximum compressive strains of - 4391 and - 7555 $\mu\varepsilon$ observed at 40 cm. The ripples in the strain profiles represent steel pipe wall deformations due to the compression of the steel pipe. With increasing of the bending loads, the valley of strain profile becomes narrow and the compression maximum is increased as well. This predicts a localized pipe-wall deformation to happen at this location, which is shown in Figure 11 after test was done.

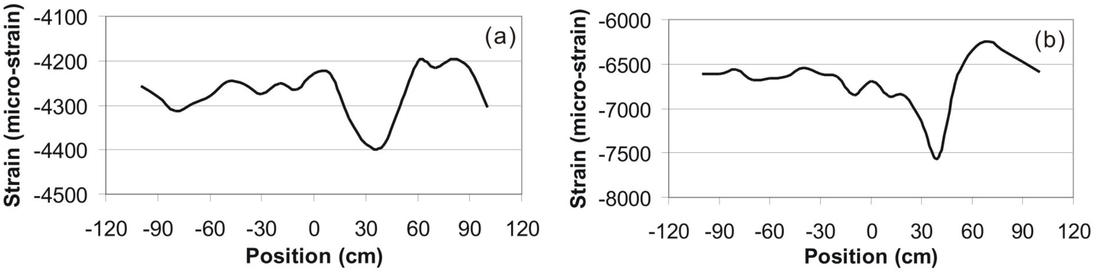


Figure 10 Strain distributions along 12 o'clock section of the steel pipe on the bending loads of 979 kN (220 kips) (a) and 1335 kN (300 kips) (b). The maximum compressive strains of – 4,391 and – 7,555 $\mu\varepsilon$ happened at 40 cm on the bending loads of 979 kN and 1,335 kN, respectively.

Figure 11. Localized pipe-wall deformation identified by a photo taken from the neutral line 9 o'clock

4. Conclusion

DSTS technology has proven to be an efficient and cost-effective solution to form an intelligent fault diagnosis system for the health monitoring and evaluation of a power grid. The results include one calendar year of monitoring a 67 km length of OPGW cable strung on high voltage power lines, achievement of high accurate temperature monitoring during H_2-cooled generator operation with seal oil system, and detection of deformation of steel structure by measuring the longitudinal strain distributions along the surface of the steel structure, which shows that 1) additional strain can be measured during significant meteorological events such as a thunderstorm or snowstorm and the effect of rime ice buildup on the OPGW cable can be also noticed; 2) hot spots only 1 cm in length for H_2-cooled generator with seal oil system can be detected when the temperature changes over 30°C and temperature profiles can clearly demonstrate that the stator zone-cooling temperature affects along the length of the fiber installed in these generators; 3) the locations of localized deformation of steel structure can be found and distinguished using their corresponding strain-load data.

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