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UTILITY APPLICATIONS OF FIBER-OPTIC DISTRIBUTED STRAIN AND TEMPERATURE SENSORS

WHITE PAPER

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INTRODUCTION

Since the early 1980's utility companies have been using optical ground wire (OPGW) in lieu of normal ground wire on high-voltage transmission lines. The basic function of the OPGW 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 optical fibers placed inside the OPGW cable are typically used for power system protection and telemetry, but have also been used for commercial applications where the capacity of the unused (dark) fibers is sold to telecom operators. The wide bandwidth, immunity to electromagnetic interference, and availability of existing right-of-way make the OPGW cable a cost-effective choice for utility telecommunications.

While OPGW cables come in different configurations, in their most basic form they consist of a central aluminum core where a bundle of optical fibers is located and wrapped with steel-reinforced aluminum strands. One of the commonly used configurations, with thousands of kilometers already installed in North America, is the tight-buffered one where optical fibers are placed inside a tight plastic buffer and then inserted in the cable core.

One important operational aspect that utility companies are facing is the harsh weather conditions to which their transmission lines are subjected, that may lead to service interruption. In the cold parts of the world, like North America and Europe, the power cables are subjected to many cycles of extreme temperatures and windstorms as well as icing conditions. In the hot parts of the world, like the Middle East and Africa, power cables are often subjected to excessive dilation due to extreme heat. In Southeast Asia and some parts of America, power transmission lines are frequently exposed to strong tropical storms and hurricanes. These weather elements increase the strain or cause rapid changes in the temperature on the transmission lines which may lead to catastrophic failures.

To detect the impact of harsh weather conditions on the availability of power systems, an effective solution is needed to proactively monitor the strain and temperature variations experienced by the transmission lines. Distributed strain and temperature sensors (DSTS) have gained interest in such applications, recently. DSTS use an optical sensing technology that is based on Brillouin optical time-domain reflectometry (BOTDR), or on Brillouin optical time-domain analysis (BOTDA), to perform both strain and temperature monitoring. DSTS uses an entire optical fiber as the sensing element, thus achieving a true distributed sensing function. Due to the low loss of optical fibers, the sensing range can approach 100 km. Taking advantage of the installed OPGW fibers to perform the sensing function can achieve remarkable savings for the utility companies.

This paper presents a brief description of the DSTS principle of operation, and discusses the experimental results of strain and temperature monitoring of an actual OPGW cable connected to a DSTS product from OZ Optics Ltd [1].

PRINCIPLE OF OPERATION

BRILLOUIN OPTICAL TIME-DOMAIN ANALYSIS (BOTDA)

Brillouin scattering stems from the density variations that dielectric materials exhibit in the presence of an electric field[1]. If an optical signal, called a probe, is injected into one end of an optical fiber, and a strong optical signal, called a pump, is injected into the other end, then the density variations induced by the electric field of the pump will result in a distributed refractive index grating inside the fiber. The distributed grating will, in turn, cause the probe to scatter in the backward direction, as shown in Figure 1.

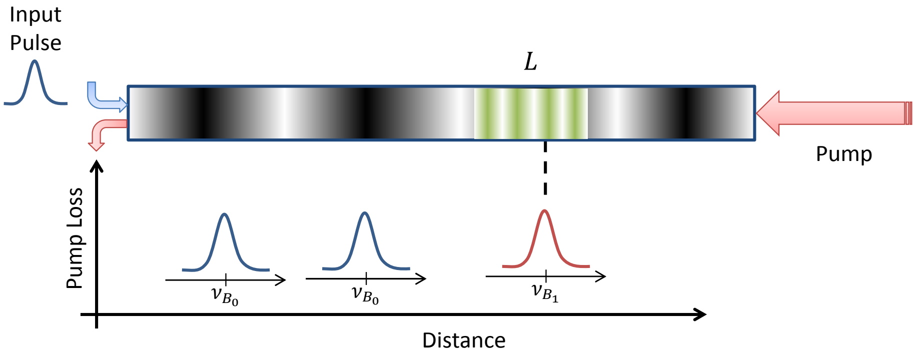

Figure 1. Brillouin scattering sensing principle.

The scattered signal is shifted in frequency by an amount ν_{B0} called the Brillouin frequency shift. For standard single-mode fibers, operated at a wavelength of 1.55 μm, the Brillouin frequency shift is approximately $\nu_{B0} \approx 11$ GHz. If a section of the optical fiber is stressed either mechanically or thermally, the Brillouin frequency shift of the scattered light from that fiber section, noted as ν_{B1} , will be different from the Brillouin frequency shift of the unstressed fiber. The amount of change in the Brillouin frequency shift is proportional to the change in temperature and/or strain. This linear dependency is typically written as [2, 3]:

$$\Delta\nu_B = \nu_{B1} - \nu_{B0} = C_t(T - T_0) + C_\varepsilon(\varepsilon - \varepsilon_0)$$

where C_t and C_ε are the optical fiber temperature and strain coefficients, respectively. For instance, laboratory measurements on ITU G.652 (SMF-28) fibers yielded the values of $C_t = 1.0241$ MHz/°C, and $C_\varepsilon = 0.0529$ MHz/με.

The BOTDA system, whose block diagram is shown in Figure 2, is based on the interaction through Brillouin scattering of a pulsed laser, acting as a probe, with a counter-propagating continuous-wave (CW) pump laser. The probe beam exhibits Brillouin amplification at the expense of the CW beam. The resultant power drop in the CW beam is measured while the frequency difference between two lasers is scanned, giving the Brillouin loss spectrum of the

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[1] This phenomenon is called electrostriction.

sensing fiber. The shift in the Brillouin spectrum of the fiber is used to calculate the temperature and/or strain change of the sensing fiber.

The BOTDA system has many features allowing it to achieve spatial resolutions as small as 10 cm and to cover sensing lengths as large as 100 km [4]. In addition, it can achieve high temperature and strain measurement accuracies of $\pm 0.1\,^{\circ}\mathrm{C}$ and $\pm 2\,\mu\varepsilon$, respectively.

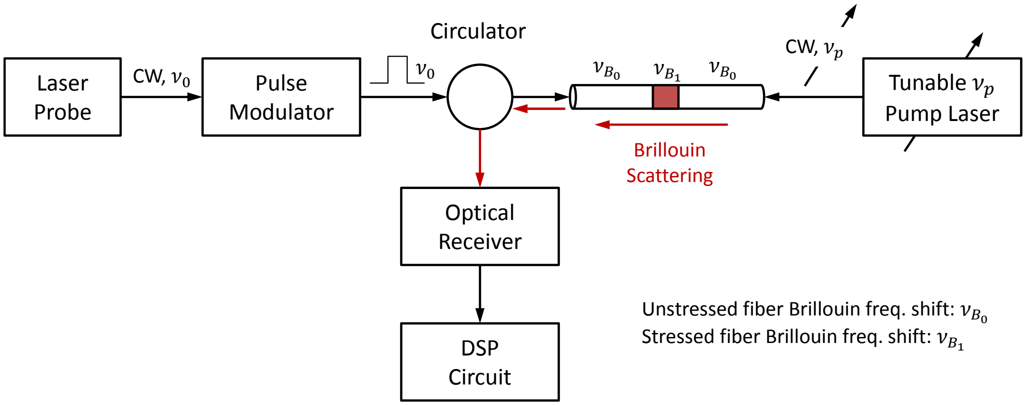

Figure 2. BOTDA block diagram.

EXPERIMENT GOAL

The overall goal of the experimental procedure was to assess the strain and temperature monitoring capabilities of the BOTDA technology when the sensing medium consisted of optical fibers located within operational OPGW cables. To achieve this goal, a field experiment was conducted in Eastern Ontario, Canada, using 67 km long OPGW cables over a period of one year from June 12, 2012 until June 17, 2013.

EXPERIMENTAL SETUP

Figure 3 shows simplified view of the experimental setup used in this paper. An OPGW cable between two power stations was used: Station "A" in Ottawa and station "B" located approximately 67 km away. Starting from station "A", the sensing medium consisted of a 1 km cabled Corning SMF-28 non-dispersion shifted fibers (NDSF) inside a dielectric jacket cable. The fibers are spliced to a 14 km segment of ITU G.652 fibers (similar to Corning SMF-28 NDSF) inside the central aluminum core of an OPGW cable. This was followed by 51 km of ITU G.653 dispersion-shifted fiber (DSF), also inside the central aluminum core of the OPGW. Finally, the route terminated 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, for the 51 km and the 14 km segments, the fiber types (G.652 vs. G.653), and the construction/composition of the OPGW cables were different, thus giving the operator the flexibility to implement this monitoring solution with mixed fibers and OPGW cable types.

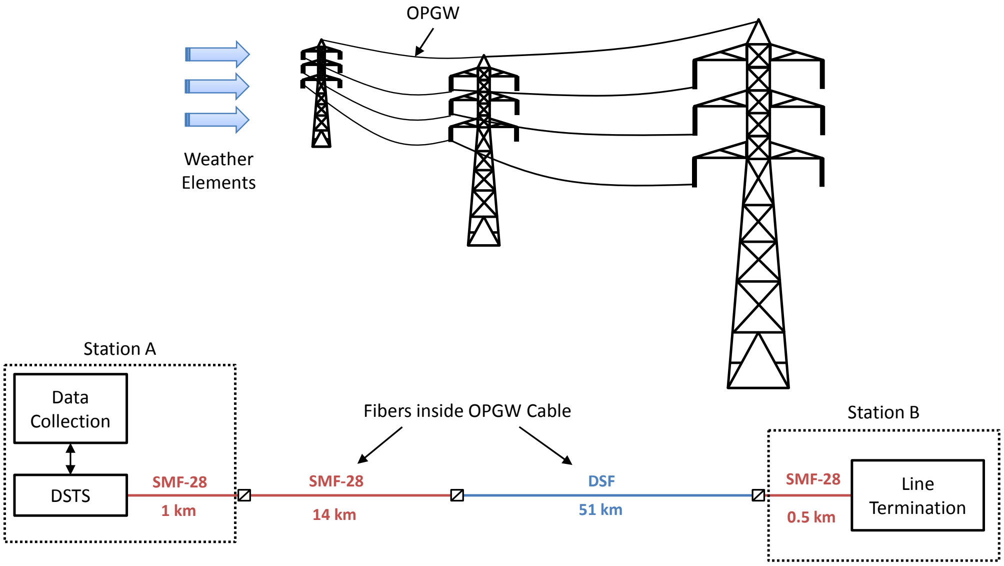

Figure 3. Simplified experimental setup of OPGW cable monitoring system using DSTS.

RESULTS

In these tests, the relative strain experienced by the OPGW (relative to the strain on the reference day of June 12, 2012 at 14:30 EDT, with outside temperature of 19 °C) was recorded and analyzed. This data takes into account the strain experienced by each fiber during the manufacturing process and installation, in addition to the strain due to weather conditions.

CABLE STRAIN DUE TO DAYLIGHT HEATING

Variations of strain on the fiber during the warm days and in transition hours from daytime to nighttime can be observed with the DSTS. During the day as the OPGW cable heats up, the cable expands and the fiber inside the cable experiences strain (despite having a helical winding). At night, the cable cools down and the OPGW contracts, thus relaxing the strain on the actual fiber inside the cable. This pattern can be observed clearly with DSTS as shown in Figure 4. Indeed, the strain on the fiber strand at 3:58 PM on a sunny June 11th day was much higher than at 3:59 AM or 6:59 AM when the ambient temperature and subsequently the OPGW cable surface temperature was much cooler.

STRAIN DUE TO CABLE CONSTRUCTION

The behavior of the first 14 km of fiber (starting from Ottawa) was different from that of the rest of the fiber due to the difference in fiber type and cable composition. This cable has SMF-28 or ITU G.652 equivalent single-mode, non-dispersion shifted fiber. The rest of the cable (excluding station cables) has dispersion-compensated (ITU G.653) fiber. ITU G.652 and G.653 fibers have different core geometries and the difference can be seen at the transition splice location at 14 km away from Ottawa in a sharp down or upslope (depending on temperature). The transition is clearly seen on the DSTS test equipment reading, as shown in Figure 5.

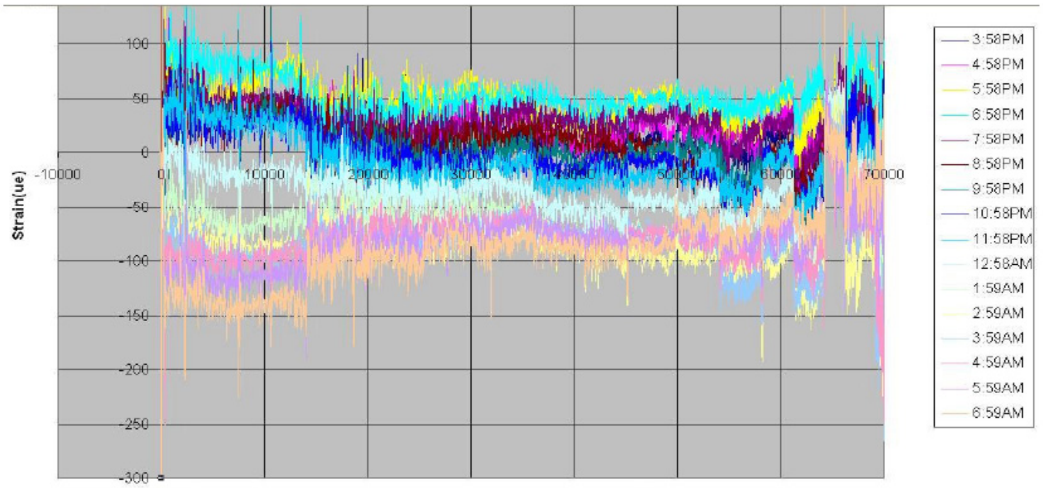

Figure 4. Typical variation of strain from daytime of June 11, 2012 till night time of June 12, 2012.

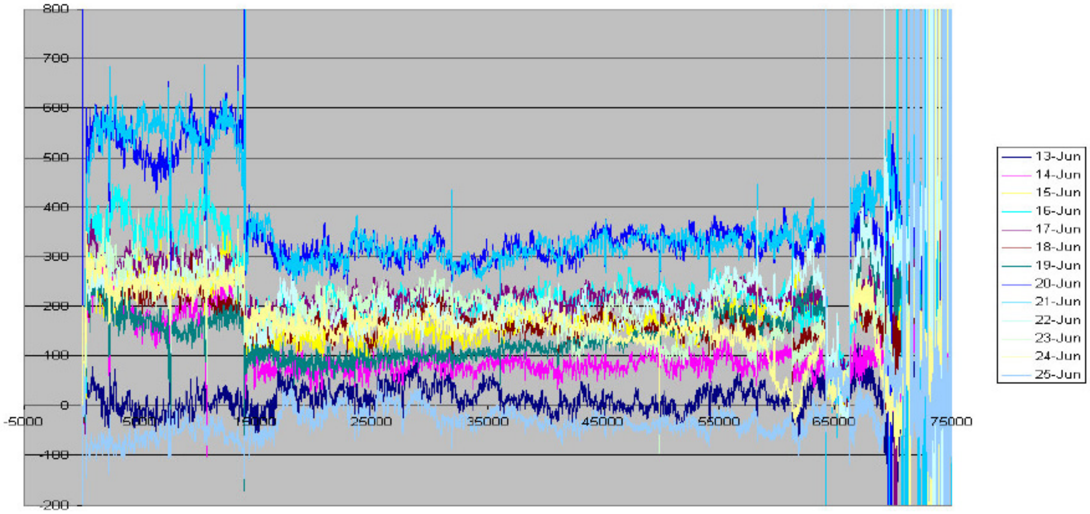

Figure 5. Measured strain values during along 67 km of OPGW (higher values for the first 14 km).

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, as shown in Figure 6. Shock cooling of the OPGW cable due to thunderstorm rain is the likely cause of this drop. The DSTS event correlates well with Ottawa's meteorological data of that day.

LONG-TERM TREND ANALYSIS

The plot of the relative strain vs. distance over a period of one month, shown in Figure 7, can provide useful trend information. The orange and red marks correspond to higher relative strain, which can be correlated to weather phenomena such as temperature and wind extremes.

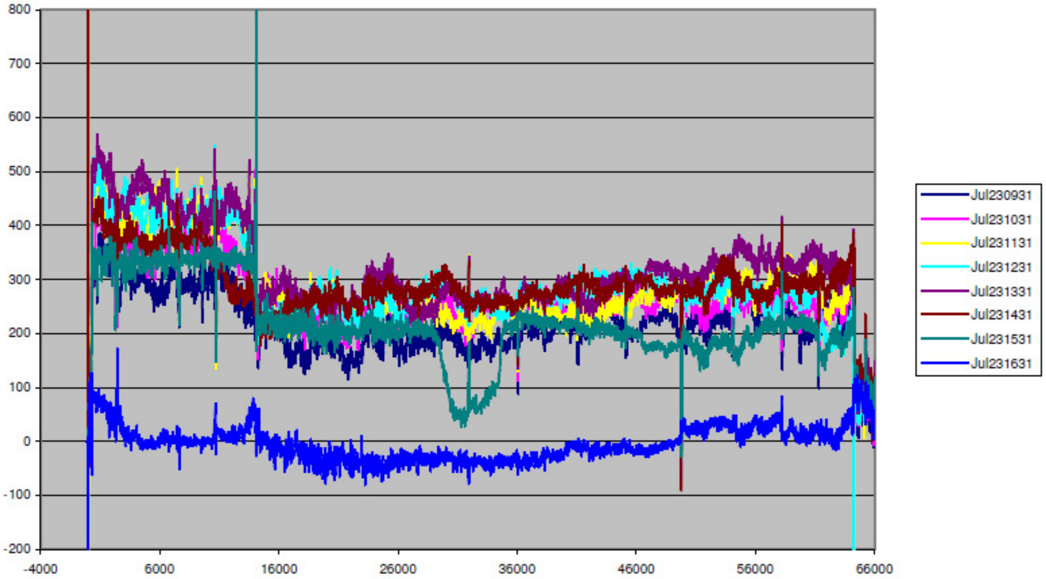

Figure 6. Strain measurements prior, during, and after a thunderstorm in the Eastern Ontario region.

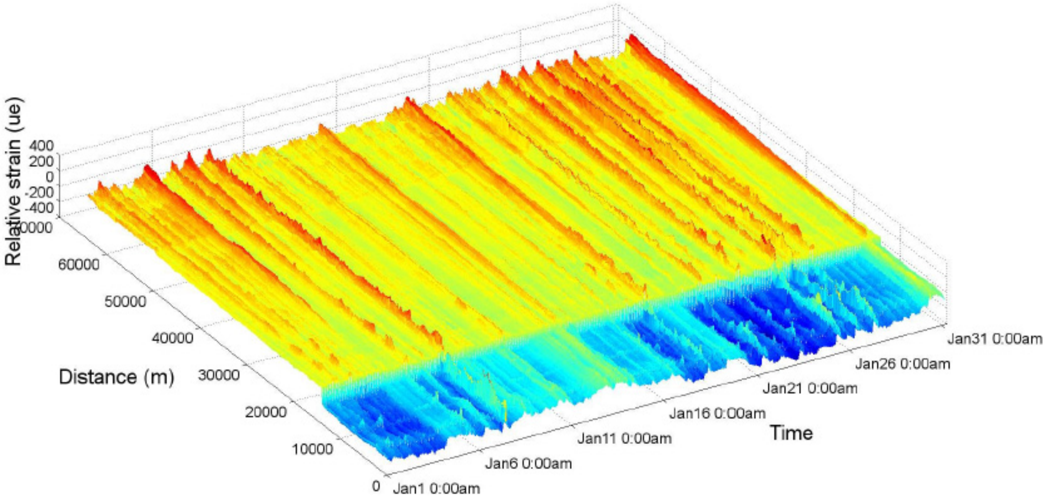

Figure 7. Relative strain variations measured by DSTS during January 2013 along the 67 km OPGW cable.

CONCLUSION

DSTS technology has proven to be an efficient and cost-effective solution to monitor weather effects on power transmission lines in utility networks. It uses optical fibers inside OPGW cables as the sensing element, thus allowing power companies to use the technology with minimal cost of installation by taking advantage of the already-installed infrastructure. The technology is capable of discerning the strain variations due to moderate daily temperature fluctuations, as well as extreme variations due to sudden weather changes as happens during storms, thus providing a useful long-term, proactive monitoring platform for power utilities.

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