Challenges and Successful Execution of Coherent Probe-Pump-Based Brillouin Sensor Applied in Industry

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Abstract: Brillouin scattering in optical fibers has been used to make distributed measurements of strain on telecommunication fibers, and to measure temperature profiles inside an air-cooled gas generator. Results of these measurements are presented.

1. Introduction

Temperature and/or strain measurements with a distributed Brillouin scattering-based sensor system provide an excellent means of health monitoring of industrial structures [1]. One class of Brillouin sensors is based on the Brillouin loss technique, whereby two counter-propagating laser beams, a pulse (probe) and a constant wavelength (pump), exchange energy through an induced acoustic field. When the beat frequency of the laser beams equals the acoustic (Brillouin) frequency, ν_B, the pulsed beam experiences maximum amplification from the pump beam. By measuring the depleted pump beam and scanning the beat frequency of the two lasers, a Brillouin loss spectrum centered about the Brillouin frequency is obtained. The sensing capability of Brillouin scattering arises from the dependence of the Brillouin frequency, ν_B, on the local acoustic velocity and refractive index in glass, which has a linear temperature and strain dependence through [2, 3]

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

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

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}. Spatial information along the length of the fiber can be obtained through optical time domain analysis by measuring propagation times for light pulses traveling in the fiber. This allows continuous distributions of the strain and temperature to be monitored. These systems offer unmatched flexibility, with the ability to monitor a virtually unlimited number of locations simultaneously.

In this work we report that DSTS systems based on coherent interaction of probe and pump lasers have been successfully employed to predict mechanical failure of fiber optic cables by measuring strain distributions along the fibers, and to monitor temperature profiles of an air-cooled gas generator by measuring the temperature distributions along the surface of the stator with 10 cm spatial resolution.

2. Mechanical failure prediction of fiber optic cables

Installation stress and long-term stress of glass fiber is limited by standards to ensure long fiber lifetime. In practice, there is no physical-chemical reason that properly designed, manufactured, and installed fiber optic cable will not last at least 25 years. The tensile strength of telecommunication grade fiber is much higher than steel. However, the strength of optical fiber is abruptly lost after prolonged exposure to moist environments [4]. Such effects are not predictable, based on early failures or OTDR measurements. Thus, mechanical failure of optical fiber must be avoided to ensure reliability of fiber-based systems. Loose optical fiber inside fiber optic cables avoids mechanical stress on the fibers. However, errors in production, processing, design, or installation have occurred around the world, resulting in mechanical failure of the optical fibers. Distributed Brillouin monitoring allows low-cost detection of slowly changing stresses that cannot be matched by other methods.

By controlling depletion of the pump beam resulting from the strong coherent interaction of the pump and probe beams, we can have good SNR for long fiber lengths. The interaction of the pump with the dc component inside the pulse length coherently interacts with the pump–pulse, resulting in pump depletion and significant amplification of the Brillouin signal. It provides localized information about the strain and/or temperature. Figure 1 displays Brillouin frequency shifts along a 23-km OPGW in Asia. The OPGW was claimed to have loose optical fibers inside. However, some optical fibers were broken in wintertime. In this particular case, two optical fibers were connected at the cursor location in the center of the graph of Figure 1. Comparing the left side of the cursor to the right side of the cursor, we can conclude the optical fibers inside the OPGW experience different stresses, indicating that the fibers were clearly not loose. This cannot be detected by an OTDR.

Figure 1: Brillouin frequency shifts along 23-km OPGW.

Errors in production can create stresses that contribute to premature mechanical failure of the fibers. An OTDR cannot provide any information about the stress on the optical fibers. For the cable in question, the OTDR shots looked fine. The design was supposed to have loose optical fibers inside the cable. However, the Brillouin frequency shifts along the fiber optic cable (Figure 1) along with the calculated strain changes (Figure 2) show the optical fibers experience non-uniform stress, as proven by the Brillouin spectrum with multiple peaks shown in Figure 3.

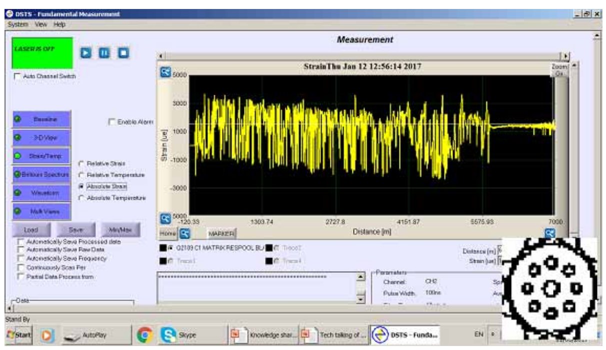

Figure 2: Calculated strain shifts along a fiber optic cable, called a fiber matrix (shown in insert).

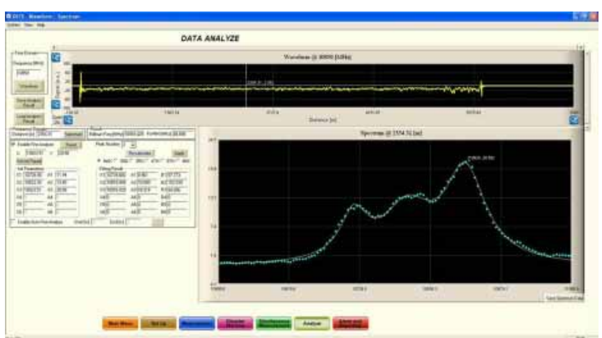

Figure 3: Brillouin spectrum with multi-peaks.

The Brillouin frequency shifts measured by the DSTS verified that the optical fibers experienced mechanical stresses, leaving the fibers prone to failure.

3. Temperature profile monitoring of an air-cooled gas generator with 10 cm spatial resolution

Gas-fired/air-cooled generators with state-of-the-art gas turbines are highly refined technology offering unmatched excellence in operation, reliability, and environmental friendliness. One yet-unsolved issue is the occasional development of hot spots in the stator core. The insulation between carbon steel laminates tends to degrade in service. Damaged insulation can cause large eddy currents to flow, leading to core damage or machine shut down as these spots proceed to heat up. 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. Current design practice does include installation of several RTDs, but these point-measuring elements are so few, and so limited in range, that the probability of detecting a core issue with one is very small.

Figure 4 illustrates the machine figuration of Siemens Westinghouse–AeroPac I–open air cooled generator showing with radially vented, zone-cooled core. Figure 5 is the distributions of temperatures along the sensing fiber measured with a 1 ns pulse duration that is equivalent to 10 cm spatial resolution. This clearly shows the temperature increasing with the loading of the generator. The temperature profiles with peaks and valleys match the radially vented, zone-cooled core of the generator

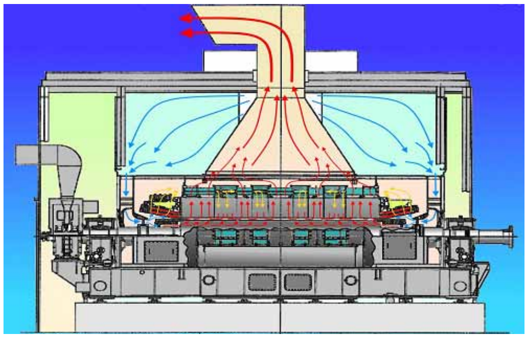

Figure 4: Machine configuration of Siemens Westinghouse–AeroPac I–open air cooled generator showing with radially vented, zone-cooled core.

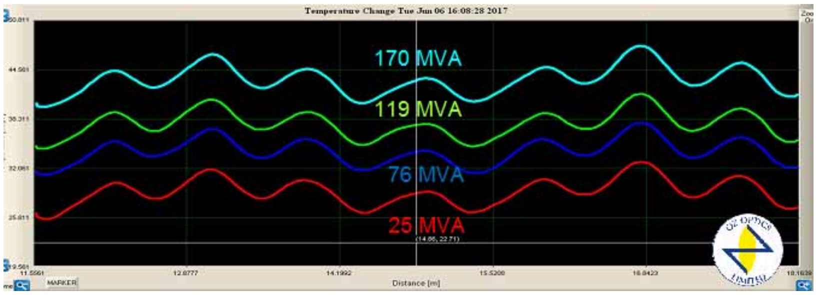

Figure 5: Distributions of temperatures along the sensing fiber set-up measured with 1 ns pulse duration. The cursor is corresponding to the loop back point of the sensing fibers.

It is cleanly shown that the temperature profile matches the designed air-cooling profile and the temperatures on the stators increase with loading that reasonably matches embedded RTDs temperature measuring from the control room.

4. Conclusions

The DSTS products based on coherent interaction of probe and pump have been successfully employed to predict mechanical failure of fiber optic cables by measuring strain distributions along the cables, and to monitor the 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 10 cm spatial resolution.

5. References

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[4] M.J. Matthewson, "Optical fiber reliability models", in Fiber Optics Reliability and Testing, Vol. **CR50** of SPIE Critical Reviews of Optical Science and Technology 1993, pp. 3-31.