Fiber-optic sensor for real-time monitoring of temperature on high voltage (400KV) power transmission lines

[1]Tarun K. Gangopadhyay, [1]Mukul C. Paul, and [2]Leif Bjerkan,

[1]Central Glass & Ceramic Research Institute (CGCRI), Kolkata, India,
[2]SINTEF (ICT), Norway.

ABSTRACT

On-line monitoring of temperature and sag in 400KV power transmission line has successfully been implemented by a novel device using fibre Bragg grating (FBG) sensors. The complete device has been fabricated with aluminum mount connected via fibre-optic cable and installed on ACSR power conductor for continuous two years measurement. This paper presents the excellent results and experience of the tests in controlled indoor environments conducted in Norway and real-field application on installed power conductor in India. Thus, better surveillance of the thermal and mechanical loads on power lines can be possible using this FBG sensor system.

Keyword: Fibre Bragg grating sensor, Temperature measurement, Power transmission lines, Instrumentation in high voltage field.

1. INTRODUCTION

In many industrialized nations the demand for electric power is steadily increasing, and the simplest way to increase power flow in existing power lines is to increase the electric current with proper monitoring facilities to overcome the following problems:

(i) A higher current causes an increased temperature of the power line. The consequence is that the conductors may age prematurely and in worst case fail because of too high temperature.

(ii) A higher temperature leads to elongation of the conductor by thermal expansion, which again leads to increased sagging of the conductor. This effect causes hazards to the ground below, and may in worst case ignite fires.

With a reliable monitoring system, in particular for some critical spans, the utility can increase the power flow to safe levels without serious risks. Presently, the maximum current flowing in a conductor is determined by a rather conservative approach based on model calculations which takes into account a number of parameters from weather phenomena and solar radiation among others. Fig. 1 shows an example of current rating which decreases with temperature.

Optical fiber technology has an advantage in high electric power environments in view of their immunity to electromagnetic fields, but low weight, small dimensions, explosion safety and the possibility to transfer signals over long distances make them also attractive. Fiber-optic Bragg gratings (FBG) are now well established techniques[1-4], basically as strain and temperature sensitive devices. FBG sensors can be configured in series or parallel fiber configurations along with the power line conductors and interrogated from remotely situated control rooms. Previously FBG sensors have been used to characterize vibrations of overhead power lines [5,6]. In this work the main goal is to construct a system for on-line monitoring of temperature and sag in power conductors with FBG sensors. This paper presents the results and experience of these initial tests in controlled indoor environments conducted in Norway and real-field application on 400KV power transmission line installed in India.

2. TEMPERATURE EFFECT ON POWER CONDUCTOR

The relationship between electric current in the conductor and its temperature is obtained from the heat balance equation which reads [7]:

$$mC_p \frac{dT_c}{dt} + q_c + q_r = q_s + RI^2 \tag{1}$$

where, mC_p is the total heat capacity of conductor (Ws/mºC), T_c is the conductor temperature (ºC), t is time (s), q_c is the convected heat loss (W/m), q_r is the radiated heat loss (W/m), q_s is the heat gain from the sun (W/m), R is the ac resistance of conductor per unit length (Ω/m) and I is the conductor current (A). In the case of indoor experiments the term q_s is zero. Since the convected and radiated heat loss terms in (1) are not linear with temperature, a numerical solution is required in order to estimate the transient behaviour. In the steady state the time dependence is zero. Fig. 2

20th International Conference on Optical Fibre Sensors, edited by Julian Jones, Brian Culshaw, Wolfgang Ecke, José Miguel López-Higuera, Reinhardt Willsch, Proc. of SPIE Vol. 7503, 75034M

shows a simulation for the actual conductor with input data taken from the IEEE standard (Std. 738-1993) with a current increase from 0-200 A and q_s=0 in (1). An ambient temperature of 20ºC is assumed. After a long time the temperature stabilizes at $T(\infty)$=24.5ºC from the electric current increase. The time to reach 99% of the equilibrium value is about 70 minutes. Inspection of the temperature behavior shows that it is close to exponential and can be fitted with a time constant τ=22.3 minutes with T(0)=20 ºC.

3. SENSOR ASSEMBLY

The final egg-shaped housing was made of aluminium in two equal halves with a hole matching the conductor diameter and could be fastened to the conductor with four screws. One half is shown in Fig. 3. Four holes are drilled into the housing from one end. An aluminium probe with diameter matching the hole as well as the diameter of the launch fiber cable is made with a groove for epoxy attachment of the FBG (one in each probe) and an accompanying splice. A picture of the probe is shown in Fig. 3 as it enters the hole in one half of the housing. Each FBG (1545 and 1550 nm) assembly was calibrated with the Micron Optics Si720 interrogator and data recorded with LAB-View based software. In the first set (Fig. 4(a)) the FBG was mounted inside the aluminium probe and it was placed in a temperature chamber. Wavelength shift and thermocouple temperature were recorded for each sensor separately. Fig. 5 shows the temperature response of FBG in the Al probe (Bragg wavelength = 1545 nm). In the figure bold and triangular data points are for rising temperature starting from ambient and empty circular data points are for downward temperature. For the second set (Fig. 4(b)) the Al probe with the FBG is placed inside the egg-shaped Al housing and then the assembly is placed on a rod heater which is specially made to mimic the conductor power. Electric current was passed through the rod heater using thyristor control arrangement and temperature was controlled using Eurotherm controller and thermocouple. Fig. 6 shows the temperature calibration of FBG embedded in the Al-mount just before the field test (Bragg wavelength = 1550 nm). Both curves are showing the same slope and behave perfectly with 0.2ºC accuracy. For this assembly the Bragg wavelength shift is dominated by the temperature expansion of aluminium and is expressed as[4]:

$$\Delta\lambda_B/\lambda_B \approx [(1-\rho_e)\alpha_S+\xi]\Delta T \tag{2}$$

where ΔT is the change in temperature experienced at the FBG location, α_S is the thermal expansion of aluminium ξ is the thermo-optic coefficient and ρ_e the photo-elastic constant. During indoor tests conducted in Norway the mount was placed on ACSR conductor and temperature increased by applying different current rating. Fig. 7 shows the conductor temperature changes by applying current at I=0, I=500A, I=700A, I=0 (recorded by thermocouple) and simultaneously wavelength shift is recorded in Fig. 8.

4. FINAL INSTALLATION ON 400KV POWER TRANSMISSION LINES AND FIELD TRIAL

After calibration the sensor system was assembled and installed at a power substation (Fig. 9) in the vicinity of Subhasgram, Kolkata operated by Power Grid Corporation, India for a complete measurement of temperature. A fiber-optic insulator is used to take the fiber-optic connection from high voltage (400KV) to ground potential (zero volts) without risk of damage to creep currents. The insulator part was hanging freely between the conductor and the tower at a safe distance below the conductors. The unit was attached with a splice box that hangs right below the conductor.

Finally the temperature measurement set up has been installed on the high voltage (400kV) power transmission line conductor of Power Grid Network in India. Fig. 9 shows the installation activity with control room in the background. The FBG interrogation system and PC are placed for temperature monitoring in a remote control room at a distance about 200 meters as shown in Fig. 9. The data logging system is directly connected with the sensors using standard fibre optic cable. The housings were installed at two different locations (Fig. 9, In-set) close to one of the towers of the same conductor which enables us to monitor temperature of the same conductor at two different points simultaneously to justify the temperature recordings. For correlation of data two sensor housings (shown in the inset) having four sensors in total are installed. Online temperature recording is going on since 27th March 2007 until now (continuously two years). The results of these tests have been excellent. The user interface of the data logging software is shown in Fig. 10 in which wavelength shifts are shown in the window and the display of temperature is showing from the data correlation of the look up table. Fig. 11 shows on-line temperature of high voltage (400KV) power conductor which is recorded during the different time of a day at the substation. It is recorded from 11.36 AM to 12.01 PM when line load was low.

5. CONCLUSION

We have developed and reported a complete temperature measurement system on the 400 KV power transmission line at Subhashgram substation of Powergrid Corporation of India using fiber-optic FBG sensors. From this sensor system sagging of the conductor can be calculated using further software which is the scope of next phase. Better surveillance of

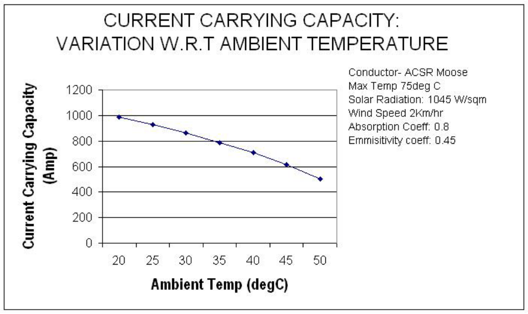

Fig. 1. A typical example of current rating decreases with temperature in a system (Courtesy: Power Grid Corporation, India).

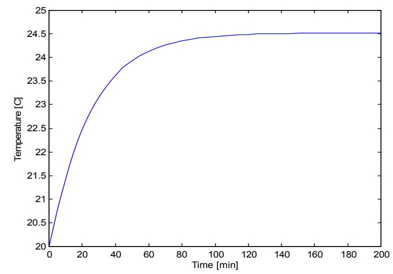

Fig. 2. Calculated conductor temperature vs. time for a FeAl 240, 26/7 conductor for a step increase of electric current from zero to 200A.

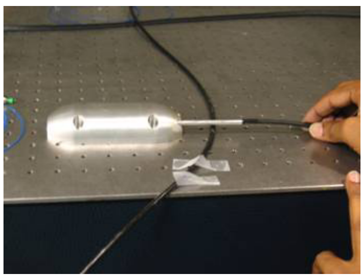

Fig. 3. Sensor mounting assembly.

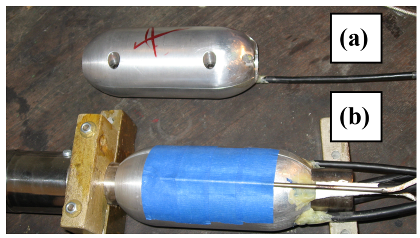

Fig. 4. FBG sensors are embedded inside an aluminium mount which is fixed on Heating element for temperature calibration.

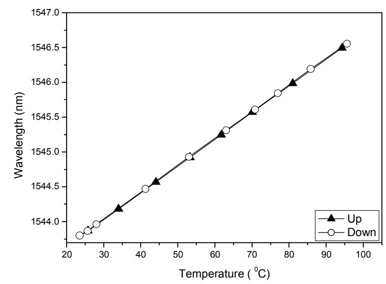

Fig. 5. Temperature calibration of FBG embedded in the Al-probe (Bragg wavelength = 1545 nm) (set 1 oven).

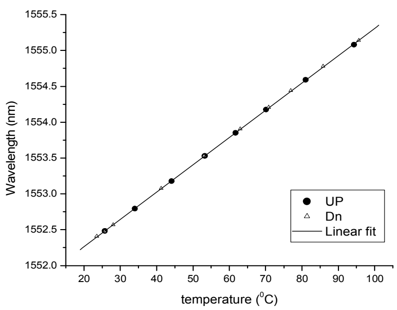

Fig. 6. Temperature calibration of FBG embedded in the Al-mount for field test (Bragg wavelength = 1550 nm) (set 2 electric heater).

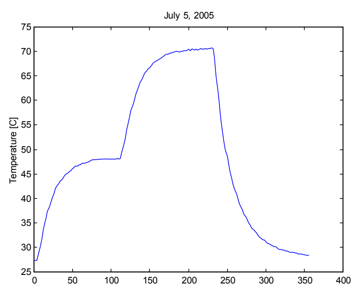

Fig. 7. Conductor temperature changes by applying current at I=500A, I=700A, I=0 (recorded by thermocouple).

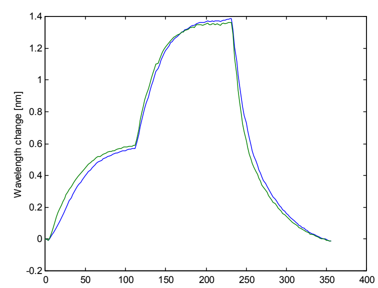

Fig. 8. Wavelength shift for two FBGs during the change of temperature (at different current such as I=500A, I=700A, I=0).

the thermal and mechanical loads on power lines can be possible using this sensor system to a more efficient utilization of the transmission capacity, enhance the reliability and provide better knowledge of the condition of the power lines and their remaining lifetime. It has been found that increase in power flow capacity by around 10% is generally possible though not 100% of the time. An increase of approximately 10 ºC in permissible conductor temperature is expected to result in an increase in power flow capacity of 25-30%.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and guidance provided by the Director, Central Glass & Ceramic Research Institute (CG&CRI), Kolkata, India. The work has been carried out under the collaborative project "IND-040

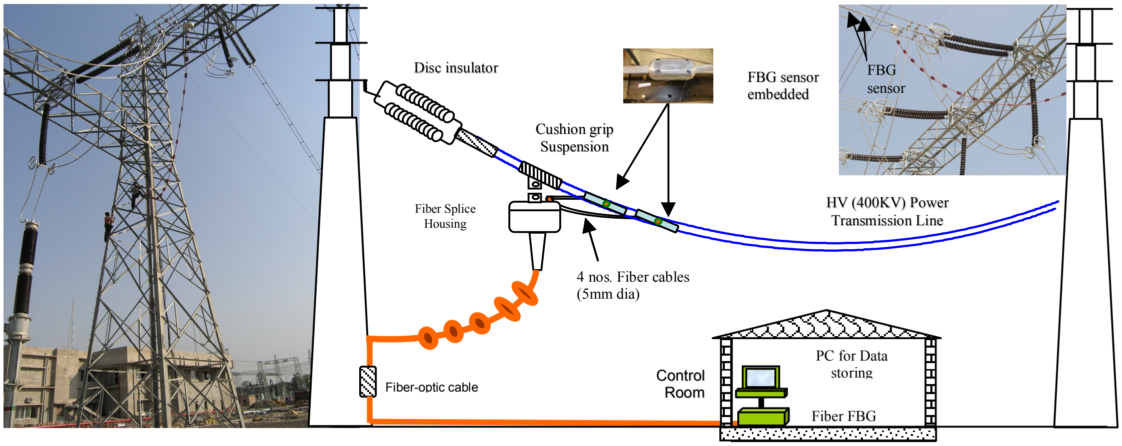

Fig. 9. Temperature measurement set-up installed on high Voltage (400KV) power transmission line conductor (In-set: Photograph of sensor mount on conductor).

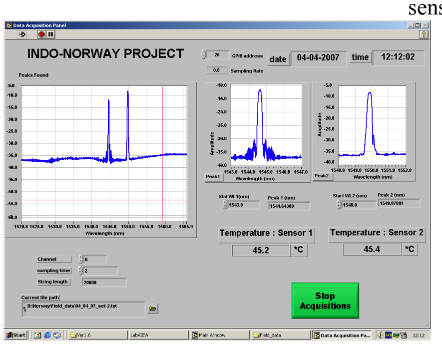

Fig. 10. On-line temperature readout of the sensors (Mount-2, Set-2, two sensors) in the control room of 400KV Power Transmission line, at Subhasgram, West Bengal, India.

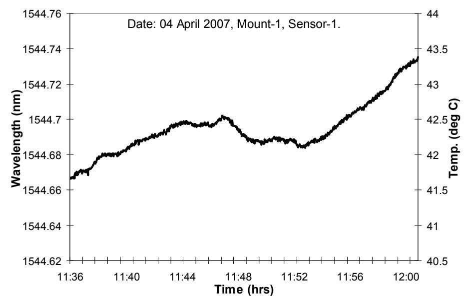

Fig. 11. On-line temperature of high voltage (400KV) power conductor recorded during the different time of a day at Subhasgram substation (when line load was low.)

Indo-Norwegian Program of Institutional Co-operation (INPIC), CLP0101. Special thanks to the Chief of Monitoring unit, INPIC for his kind help in funding and support. The authors would also like to acknowledge the support of all engineers of Powergrid Corporation of India specially to provide the space and facilities in Subhasgram substation (near Kolkata) during field trials. Authors would like to acknowledge the support of Optical Fibre Laboratory, CGCRI, specially Mr. Kamal Dasgupta (HOD), Dr. Somnath Bandyopadhyay, Mr. Palas Biswas and Dr. Shyamal Bhadra.

7. REFERENCES

[1]. Y.J. Rao, "Recent progress in applications of in-fibre Bragg grating sensors", Optics Lasers Eng. (**31**), 297–324, 1999.

[2]. M. Majumder, T. K. Gangopadhyay, A.K. Chakraborty, K. Dasgupta and D.K. Bhattacharya, "Fibre Bragg Gratings as Strain Sensors- Present Status and Applications", Sensors and Actuators A: (**147**), pp.150-164, 2008.

[3]. T. K. Gangopadhyay, M. Majumder, A.K. Chakraborty, A.K. Dikshit and D.K. Bhattacharya, "Fibre Bragg Grating strain sensor and study of its packaging material for use in critical analysis on steel structure", Sensors and Actuators A: (**150**), pp.78-86, 2009.

[4]. L. Yu-Lung and C. Han-Sheng, "Measurement of thermal expansion coefficients using an in-line Bragg grating sensor", Meas. Sci. Technol. (**9**), 1543-1547, 1998.

[5]. L. Bjerkan: "Application of fiber-optic Bragg grating sensors in monitoring of environmental loads of overhead transmission lines", Applied Optics, (**39)**, 554-560 (2000).

[6]. L. Bjerkan, O. Lillevik, S. M. Hellesø, S. Enge and K. Halsan, "Measurements on aeolian vibrations on a 3 km Fjord Crossing with Fibre-Optic Bragg Grating Sensors", Proc. Cigré Session 2004, paper B2-314.

[7]. IEEE Std. 738-1993, "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors", IEEE, USA, 1993.