Distributed Fiber Optic Sensing and Dynamic Rating of Power Cables

Sudhakar Cherukupalli
George J. Anders

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This book would not have been possible without the love, sacrifice, and inspiration received throughout my life from my beloved mother Annapurna and father Gopalakrishna.

The second author would like to thank his wife Justyna for a continuous support and understanding and would like to dedicate this book to his grandchildren Sophia and Anthony Anders.

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Preface

The subject of the book is the theory and practical applications of dynamic temperature sensing (DTS) in the context of high voltage (HV) power cables. The book is addressed to cable system design engineers, cable manufacturers, electric power system operators, engineering students, and scientists. This is the first book addressing a subject of the application of the DTS in HV power cables. DTS systems are used to obtain the temperature readings from the fiber optic sensors either built-in within the cable or placed on its surface or in close vicinity. Great majority of new HV cables are manufactured today with the fiber built-in. However, in order to take full advantage of this technology, the owner of the cable needs to familiarize himself/herself with the possibilities it offers. Hence, the book explains the physics of the DTS measurements and offers plenty of practical information about the costs, installation procedures, maintenance, and various applications – focusing on dynamic cable ratings.

The book is aimed as a primary source about the new area of temperature measurements for many different groups. The first group are cable manufacturers, who not only produce the cables with fiber optic links but also often offer the DTS and real time thermal rating (RTTR) systems themselves. The second group will be the DTS manufacturers. There are many companies around the world offering this technology. They usually understand the physics of the temperature sensing but have a limited knowledge of the utility practices, test and quality requirements, and possible rating applications.

The book is also addressed to the cable engineers. These will be utility personnel, contractors, and cable system designers. They usually understand the need for such systems, their output, and test requirements. However, they may lack the knowledge of the physics involved and the book will help them in understanding the opportunities and the limitations of the technology.

Another important group of readers will be comprised of the university students and their teachers. The book will help them appreciate the utility perspective in the application of the DTS technology. The book also has the classroom potential. It would particularly be useful for all the courses related to cable technology. This would include courses on cable construction, heat transfer phenomena in power cables, calculation of current ratings of electric power cables, and also design of ac and dc submarine cables that are being increasingly used to interconnect export from off-shore wind parks.

Considering the advantages that fiber optic sensors have to offer, it is not surprising their proliferation in a wide variety of modern industries. This book concentrates on the application of this technology in the electric power systems. It is organized as follows:

Chapter 1 contains introduction to fiber optic sensing with examples of several application fields not related to the power systems.

Chapter 2 provides a brief overview and talks about the distinction between single point and distributed measurements and discusses the advantages and disadvantages each of such systems offer.

Chapter 3 discusses the concept of distributed temperature sensing and describes what constitutes such a system as well as its architecture as used in the electrical power industry.

Chapter 4 introduces the reader to the optical fibers, connectors, optical cable construction, and provides some illustrations of these systems.

Chapter 5 provides examples of how optical fibers are incorporated into the land and submarine cables. It also discusses the advantages and disadvantages of various fiber locations inside and outside the power cable.

Chapter 6 discusses the DTS system requirements and reviews the standards for the electromagnetic compatibility. It presents the architecture of a DTS system and how it is integrated into a utility environment. Some of the challenges with this integration and data interpretation are also discussed.

Chapter 7 provides information of the importance of site testing of a DTS system and challenges that a utility may face with the site commissioning tests.

Chapter 8 discusses the relevance and importance of the DTS system calibrators. It also reviews the benefit of such systems and talks about the maintenance issues.

Chapter 9 illustrates how the temperature data may be utilized by the asset owner to optimize the use of their resources and discusses the dynamic circuit ratings of power cables with the data provided by a DTS system.

Chapter 10 Provides several examples of application of DTS systems in a utility environment. It includes a description of retrofitting of the fiber optic cables into existing cable circuits.

Chapter 11 provides some examples of potential future uses of the distributed fiber optical cable system for strain measurement and acoustic applications in power cables.

A large part of the material covered in this book was derived from various projects conducted by British Columbia Hydro (BCH) and from the work performed by various CIGRE and IEEE Working Groups of which the authors of this book were the members. The authors are indebted to Landry Molimbi and Masaharu Nakanishi, members of the CIGRE WG B1.45, who provided background material used in Chapters 4, 7, and 8 of this book. Frequent discussions with DTS vendors contributed greatly to the development of many procedures described herein. In addition, we could have not written this book without an involvement and close association with several individuals who contributed their ideas and took the time to read the manuscript. We are particularly indebted to Dr. M. Ramamoorty and Chris Grodzinski, who have reviewed the entire manuscript and provided several helpful comments.

We would also like to acknowledge the support the authors have received from the Standards Council of Canada (SCC) and several Senior Managers from BCH, as well as the financial assistance of SCC and BCH in supporting our participation in the activities of WG 10 of the IEC and WG B1.45 of CIGRE over many years.

Finally, but by no means last, we would like to thank our families who supported wholeheartedly this endeavor.

Vancouver and Toronto

Sudhakar Cherukupalli
George J. Anders

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Dr. Sudhakar Cherukupalli would like to acknowledge retired colleagues from BC Hydro and in particular Joseph Jue, Allen MacPhail, and Takashi Kojima for their support during the world's first installation to harness DTS technology on a 525 kV submarine cable system.

1

Application of Fiber Optic Sensing

Today, fiber optic (FO) sensors are used to monitor large composite aircraft structures, concrete constructions, and to measure currents in high-voltage equipment. They are also applied in electrical power industry to measure electric fields as an alternate to current and voltage transformers. They are also finding many applications in the field of medicine, chemical sensing, as well as to monitor temperatures around large vessels in the oil and gas processing industries. There have been recent attempts in Japan to monitor the wings of a fighter aircraft to monitor dynamic strain and temperatures when the aircraft is taking off and landing to better understand the load and temperature-induced stresses and how these affect fatigue performance. Considerable work is underway to map strain in large composite and concrete structures.

Research on the application of FO sensors (FOSs) has been conducted over many years. They were first demonstrated in the early 1970s (Culshaw and Dakin 1996; Grattan and Meggitt 1998) and are the subject of considerable research since 1980s. Early applications were focused on military and aerospace uses. FO gyroscopes and acoustic sensors are examples, and they are widely used today. With the increase in the popularity of FOSs in the 1980s, a great deal of effort was made toward their commercialization with an emphasis on the intensity-based sensors. In the 1990s, new technologies emerged, such as in-fiber Bragg grating (FBG) sensors (Morey et al. 1989; Rao 1997), low-coherence interferometric devices (Grattan and Meggitt 1995; Rao and Jackson 1996), and Brillouin scattering distributed sensors (Bao et al. 1995). Dramatic advances in the field of FO sensors have been made as a result of the emergence of these new technologies leading to a significant proliferation of their use.

FO sensors offer significant advantages over conventional measuring devices, most important of which are: electromagnetic immunity (EMI), small size, good corrosion resistance, and ultimate long-term reliability. For example, FBG sensors offer a number of distinguishing advantages including direct absolute measurement, low cost, and unique wavelength-multiplexing capability.

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These new measuring technologies have formed an entirely new generation of sensors offering many important measurement opportunities and great potential for diverse applications.

This book is devoted to the application of the FO technology in electric power cables. However, before we tackle this subject, we would like to offer a brief review of the application of this technology in other fields. In the following sections, an attempt is made to provide an overview of the types of FO sensors and we will list some of the industries where FOSs have been applied. These include:

- Oil and gas industry
- Fire detection and integrating them with the firefighting equipment
- Large composite structure such as bridges and dams
- Mines
- Aircraft industry
- Medicine
- Power industry

1.1 Types of Available FO Sensors

One of the first applications of FOSs involved the, so-called, limit sensors with an ability to detect motion beyond a certain limit and initiate action once this limit is exceeded. These types of sensors can be used for monitoring linear or rotational motion. Another type of an early application is a level sensor when a solid or a liquid rises or falls beyond a set point. Proximity sensors use infrared emission, reflection, or pressure change to perform such detection without the need for any physical contact. Another example involves a beam of light crossing a doorway. Beam interruption can be detected by a photo sensor and trigger an alarm. This application is typically used in the process industry for counting or having access control.

Another class of sensors uses FOs for linear or angular position control. One may have an array of optical fibers that are placed in parallel. The object to be detected when passing this array of sensors may alter the transmission or reflection of light. The sensor processing electronics can then infer the proper position of each object within the sensing region. In this case, the resolution of the detected positions will depend on the spacing between the sensing points. This idea has been extended by placing fibers in an angular fashion and has been used to detect or establish the angular position of a gear on drive systems.

FO sensors have also been used to measure linear as well angular speed or velocity of shafts (tachometers). Some of them use Doppler phase shift methods for such measurements.

A FO gyroscope is another type of sensor. It consists of a coil, either polarization preserving or not, of optical fibers in which the light is simultaneously propagating in the clockwise and counterclockwise directions. The SAGNAC effect induces a differential phase shift between the clockwise and counterclockwise guided waves in the rotating media. The phase difference in the detected signal is converted into a rate or angle of rotation. Examples of this application are the Brillouin or resonant FO gyroscopes.

Optical fibers have also been used for temperature sensing. They may be broadly classified as FBG devices. Phosphor coated, Fabry–Perot cavity terminated, or thermo-chromatic terminated optical fibers are some examples of such point sensors. In the electric power industry, these devices have been used to measure transformer winding temperatures.

Another class of temperature sensors are the distributed FO temperature devices. These are broadly classified as based either on the Raman scattering or Brillouin principles. Laser light injected into a fiber is continuously scattered. This backscattered light is used for calculating temperature profiles along the fiber. Brillouin scattering exhibits sensitivity to temperature as well as strain, so care has to be exercised when interpreting the temperature data. Devices based on Raman scattering fall into two principal categories: those that rely on the optical time domain reflectometry (OTDR) while the others use the optical frequency domain reflectometry (OFDR). It is the latter that provides the highest spatial resolution along a fiber.

While discrete monitoring based on FBG FO system has been and is continued to be used, it is expected that the distributed FOSs will play a more important role in health monitoring of large structures, such as dams, because the use of a single fiber makes installation easy with the ability to measure over long distances. While considerable advances have been made in measuring strain, the effects of temperature-induced strain appear elusive especially when one needs to improve spatial resolution and accuracy. Because of its complexity, simultaneous measurement of multi-axis strain and temperature in composites remains a major challenge for the optical fiber sensors community.

Because of a spate of explosive in-service failures of the 525 and 800 kV oil-filled current transformers in the late 1990s, the industry was looking for alternate devices that could provide accurate current measurements with a dynamic rating ranging from several 1000s to several 100 000s amperes. This led to the development of FO electric current sensors based on the Faraday effect. After more than two decades of development, they have successfully entered the market. At the University of British Columbia in Canada, Dr. Jaeger and his research team developed an electric field or voltage sensors and had conducted several field tests to prove the concept and develop a practical system. These systems were placed in the local utility's 500 kV substation on a trial basis (Jaeger et al. 1998). Further collaborative efforts led to the development of integrated electro-optic voltage and current sensors. Initially, the challenge with these systems appeared to be their inability to match the needs of the conventional protection equipment that required 120 V and 5 A input signals. In parallel, the modernization of the electric power grid and changes that occurred with the development for solid-state relays, which now require lower voltage (~5 V) and current signals (100 mA), the devices developed at the university became more appealing to the industry. Moreover, these electro-optical devices provided higher sensitivity, improved frequency bandwidth, with significantly improved EMI. This led to general acceptance of electro-optical devices for current and voltage measurements in the power industry.

For medical applications, extrinsic FOSs based on multimode fiber transmission have matured. A number of FBG temperature and ultrasound sensor systems have been developed. With further engineering, it is anticipated that these systems could be used for in-vivo measurement of temperature or/and ultrasound as well as blood pressure in the heart and other organs. In chemical sensing, FOSs based on evanescent wave coupling is still under development.

The following sections describe in more detail the application of the FO sensors in various industries.

1.2 Fiber Optic Applications for Monitoring of Concrete Structures

When compared with traditional electrical gauges used for strain monitoring of large composite or concrete structures, FOSs have several distinguishing advantages, including:

- A longer lifetime, which could probably be used throughout the working lifetime of the structure (e.g. >25 years) as optical fibers are reliable for long-term operation over periods greater than 25 years without degradation in performance.
- A greater capacity of multiplexing a large number of sensors for strain mapping along a single fiber link, unlike strain gauges, which need a huge amount of wiring.
- Greater resistance to corrosion when used in open structures, such as bridges and dams.
- A much less intrusive size (typically 125 mm in diameter – the ideal size for embedding into composites without introducing any significant perturbation to the characteristics of the structure).
- A much better invulnerability to electromagnetic interference, including storms, and the potential capability of surviving in harsh environments, such as that encountered in the nuclear power plants (Townsend and Taylor 1996).

These features have made FOSs very attractive for quality control during construction, health monitoring after building, and impact monitoring of large composite or concrete structures (Udd 1995). Since the use of FOSs in concrete was first suggested in 1989 (Mendez et al. 1989) and the demonstration of embedding a FO strain sensor in an epoxy–fiber composite material was reported in the same year (Measures 1989), a number of applications of FOSs in bridges, dams, mines, marine vehicles, and aircraft have been demonstrated.

One of the first monitoring demonstrations for large structures using FOSs was a highway bridge using carbon fiber-based composite prestressing tendons for replacement of steel-based tendons to solve a serious corrosion problem (Measures et al. 1994). Because composite materials are not well proven in their substitution for steel in concrete structures, there is considerable interest in monitoring the strain and deformation or deflection, temperature, or environmental degradation within these materials using an integrated FO sensing system. FBG sensors could be suitable for achieving such a goal. An array of FBGs has been attached to the surface of a composite tendon and the specially protected lead-in/out optical fibers egress through recessed ports in the side of the concrete girders, as shown in Figure 1.1. However, if the FBG sensors could be embedded into the composite tendons during their manufacture, excellent protection for the sensors and their leads would be provided and done by (Measures et al. 1997).

Dams are probably the biggest structures in civil engineering; hence, it is vital to monitor their mechanical properties during or/and after construction in order to ensure the construction quality, longevity, and safety. FOSs are ideal for health monitoring applications of dams because of their excellent ability to be used in long-range measurements. Truly distributed FOSs are particularly attractive as they normally have tens of kilometers measurement range with a meter spatial resolution. A distributed temperature sensor has been demonstrated for monitoring concrete setting temperatures of a large dam in Switzerland (Thevenaz et al. 1999). This monitoring is of prime importance as the density and microcracks are directly related to the maximum temperature the concrete experiences during the setting chemical process.

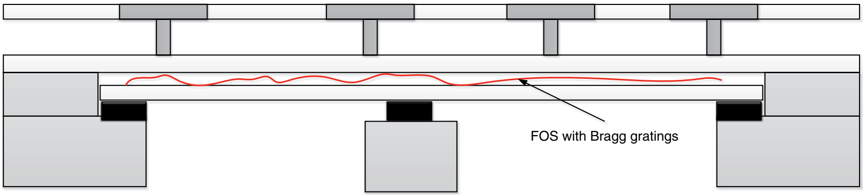

Figure 1.1 Schematic diagram of a fiber Bragg grating sensor locations for strain monitoring on a bridge.

This system has been used for concrete setting temperature distribution in a slab with dimensions of 15 m (L) × 10 m (W) × 3 m (H). These slabs are used for estimating the height of the dam in order to increase the power capability of the associated hydroelectric plant. The layout of an optical communication cable inside the slab is shown in Figure 1.2, which gives a two-dimensional temperature distribution of the whole area. The fiber cable is installed during the concrete pouring. Figure 1.3 shows the temperature distribution over the slab at different times after concreting. It reveals that the temperature at the central area of the slab can be as high as 50 °C and it takes many weeks for this region to cool down.

Many research groups have demonstrated the "simple" operation of FBGs embedded in large composite or concrete structures for strain measurement. However, further work may be needed in order to produce a cost-effective, multifunctional FBG multiplexing system that is able to measure static strain, temperature, and dynamic strain simultaneously with adequate resolution and accuracy. With such system, the FBG sensor would be able to realize its full potential and perhaps dominate the market for health monitoring of large composite and concrete structures in the future.

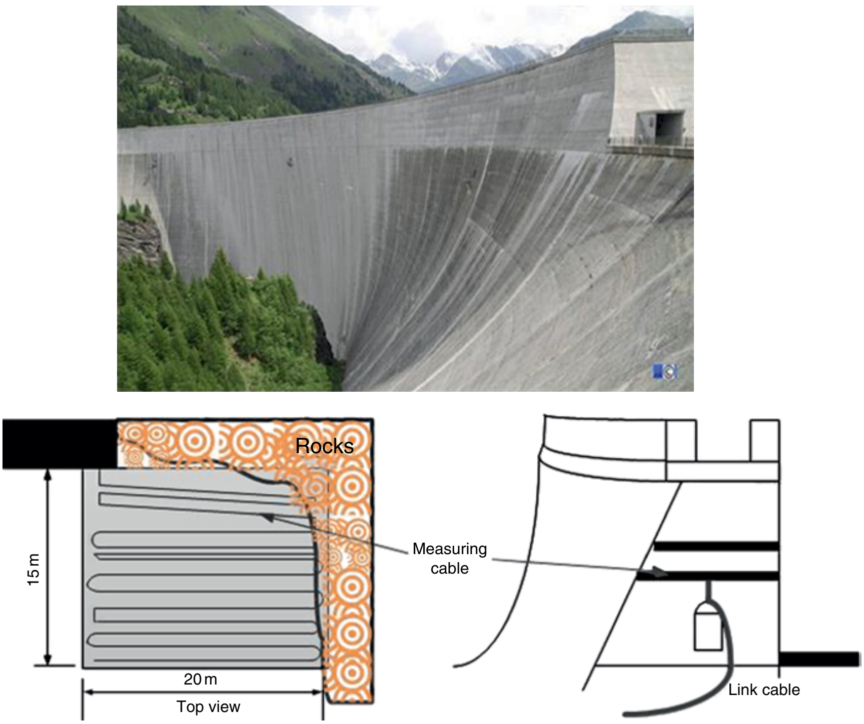

Figure 1.2 Layout of an optical communication cable inside a concrete slab.

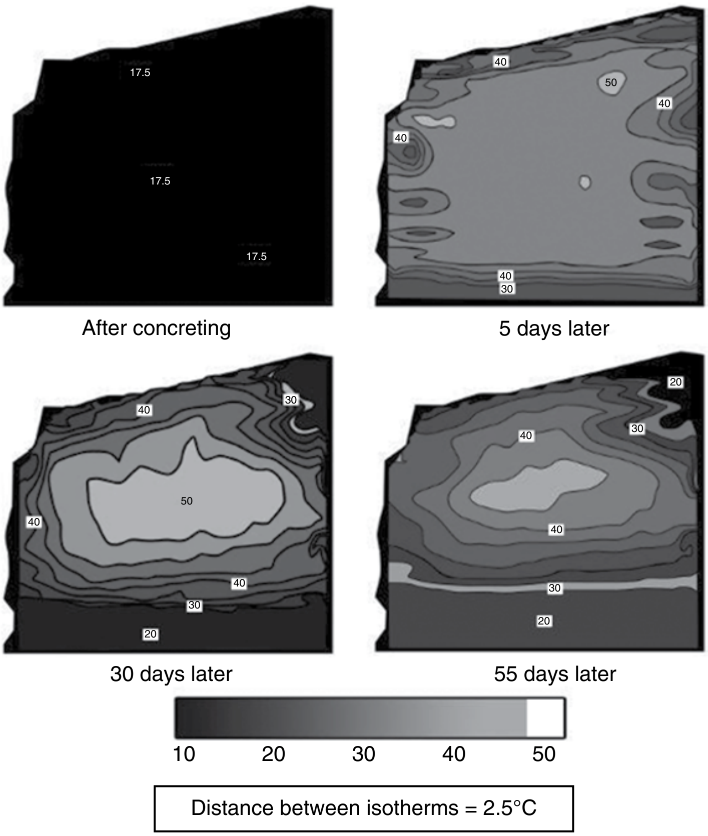

Figure 1.3 Two-dimensional temperature distribution in Luzzone dam during the concrete curing obtained with embedded fiber using Brillouin sensor.

1.3 Application of FO Sensing Systems in Mines

Measurement of load and displacement changes in underground excavations of mines and tunnels is vital for safety monitoring. Multiplexed FBG sensor systems could replace the traditional electrical devices, such as strain gauges and load cells, which cannot be operated in a simple multiplexed fashion and in a very hazardous environment with strong electromagnetic interference generated by excavating machinery. An FBG sensor system based on a broadband Erbium-doped fiber source and a tunable Fabry–Perot filter has been designed for long-term static displacement measurement in the ultimate roof of the mining excavations and in the hanging wall of the ore body's mineshaft (Ferdinand et al. 1995). A specially designed extensometer with a mechanical-level mechanism can cope with the large displacements of up to a few centimeters