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SPIE—The International Society for Optical Engineering

Fiber Optic and Laser Sensors IX

Ramon P. DePaula
Eric Udd
Chairs/Editors

3-5 September 1991
Boston, Massachusetts

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FIBER OPTIC AND LASER SENSORS IX

Volume 1584

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Session 1—Industrial Applications of Fiber Optic Sensors
John W. Berthold III, Babcock & Wilcox Company

Session 2—Fiber Optic Temperature Sensors
Eric Udd, McDonnell Douglas Electronic Systems Company

Session 3—Fiber Optic Current Sensors
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Conference 1584, *Fiber Optic and Laser Sensors IX,* was part of a six-conference program on Sensors held at SPIE's OE/Fibers '91, 3-6 September 1991, in Boston, Massachusetts. The other conferences were:

Conference 1585, *Fiber-Optic Gyros: 15th Anniversary*
Conference 1586, *Distributed and Multiplexed Fiber-Optic Sensors*
Conference 1587, *Chemical, Biochemical, and Environmental Fiber Sensors III*
Conference 1588, *Fiber Optic Smart Structures and Skins IV*
Conference 1589, *Specialty Fiber-Optic Systems for Mobile Platforms and Industry.*

Program Chair: **Ramon P. DePaula,** NASA Headquarters

INTRODUCTION

The field of fiber optic sensors has expanded rapidly over the past 12 years, and SPIE-sponsored conferences have grown with it. The first fiber optic sensor conference sponsored by SPIE was the Laser Inertial Rotational Sensor conference in 1978, chaired by Shaoul Ezekiel and G.E. Knausenberger; roughly half of its 30 papers were devoted to topics related to fiber optic gyroscopes. After this initial conference, fiber optic sensor papers were dispersed to many SPIE conferences, including those on integrated optics, single-mode optical fibers, and guided-wave optical systems and devices. In 1983, Emery Moore and Glen Ramer pulled these papers together into the Fiber Optic and Laser Sensor series of conferences that have formed the backbone of the OE/Fibers Fiber Optic Sensor program. In 1985, to better serve the strong European fiber optic sensor community, Herve Arditty and Luc Jeunhomme started the Fiber Optic Sensors conference series. This expansion in the baseline program was strongly complemented in 1986 by the addition of two specialty fiber optic sensor conferences, Fiber Optic Gyros: 10th Anniversary Conference, and High Bandwidth Analog Applications of Photonics.

In 1988, the OE/Fibers symposium was structured with the first two days devoted to the baseline Fiber Optic and Laser Sensors VI conference, including introductory tutorial invited papers, followed by three specialty conferences running in parallel for two days: Fiber Optic Smart Structures and Skins; High Bandwidth Analog Applications of Photonics II; and Chemical, Biochemical, and Environmental Applications of Fibers.

In 1989, the OE/Fibers symposium in Boston continued the basic format, with Fiber Optic and Laser Sensors VII acting as the general conference devoted to generic fiber optic sensor development, complemented by four specialty conferences that ran in parallel: Fiber Optic Smart Structures and Skins II; Chemical, Biochemical, and Environmental Fiber Sensors; Fiber Optic Systems for Mobile Platforms III; and Fiber Laser Sources and Amplifiers. Combined, these conferences represented a significant increase in scope, resulting in a Fiber Optic Sensor program with over 240 papers.

In 1990, the OE/Fibers symposium in San Jose continued the same tradition of OE/Fibers '88 and '89. Fiber Optic and Laser Sensors VIII acted as the focus conference devoted to generic fiber optic sensor development and was complemented by six additional specialty conferences that ran in parallel: Fiber Optic Smart Structures and Skins III; Chemical, Biochemical, and Environmental Fiber Sensors II; Fiber Optic Systems for Mobile Platforms IV; Fiber Laser Sources and Amplifiers II; and Integrated Optics and Optoelectronics II. As in 1989, these conferences presented a broad-scope program in fiber optic sensor technology with about 240 papers.

The OE/Fibers '91 symposium returned to Boston, following the same tradition of OE/Fibers '88, '89 and '90. Fiber Optic and Laser Sensors IX acted as the focus again, and was complemented by the specialty conferences. This year we had one additional specialty conference, Fiber Optic Gyro: 15th Anniversary Conference. About 260 papers were presented at these conferences, providing an excellent cross-section of fiber optic sensor technology.

We would like to thank all the cochairs, speakers, and SPIE staff for making this conference and proceedings a success.

Ramon P. DePaula
NASA Headquarters

Eric Udd
McDonnell Douglas Electronic System Company

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SESSION 1

Industrial Applications of Fiber Optic Sensors

Chair

John W. Berthold III
Babcock & Wilcox

Introduction to industrial application session

John W. Berthold

The Babcock & Wilcox Company, Research and Development Division
1562 Beeson Street, Alliance, Ohio 44601-2196

At this conference in 1988, I asked the question, "Why buy fiber optic sensors?". At that time, I tried to look at the technology from the user's viewpoint. I identified many issues that seemed to impede implementing fiber optic sensor technology in industrial applications. Two leading obstacles were sensor cost and customer fear of the unknown. These impediments are still present, albeit to a lesser extent. And as the technology and experience base have advanced over the past three years, other obstacles (lack of standards, for example) that had earlier prevented use of fiber optic sensors in industry are quickly disappearing.

I will briefly discuss some of the remaining issues and roadblocks to this implementation, but I also want to emphasize the great amount of progress that has been made in practical applications of fiber optic sensors in industry, as witnessed by the good cross-section of papers to be presented in this Industrial Applications Session. I continue to be optimistic that in a few years, fiber optic sensor technology will be widespread, but for now, successful applications of fiber optic sensors continue to be in special niche areas — where the technology has an advantage over conventional sensors.

The results of one intriguing survey by Automation Marketing Strategies Inc. were summarized by Alphonse Vitale in the January 1991 issue of *Photonics Spectra*. In that survey, 62% of end users and 56% of OEMs cited lack of knowledge of fiber sensor technology, not cost, as the primary obstacle to applications. The reason given for this lack of knowledge appears to be uniquely American; that is, difficulty in introducing incremental improvements, compared to relative ease with which American companies can introduce revolutionary new technology. This conclusion indicates that suppliers of fiber sensors should put greater emphasis on training, hands-on implementation, and marketing strategies — such as offering products at no cost to selected customers in return for testimonials.

Most important, these suppliers must be willing to bend over backward to address customer concerns and satisfy special needs. Concerns such as performance encompass not just the sensor specifications, but issues such as standards and recalibration requirements as well. Cost issues must consider indirect factors such as component sharing and insurance savings as well as the direct costs for hardware, installation, and spare parts.

Reliability issues are not limited to life expectancy only, but also include aging characteristics, expected failure modes, and degradation mechanisms. The data acquisition and control system with which fiber sensors must communicate put certain constraints on the sensor output to ensure compatibility with existing customer equipment.

Fiber sensor technology will continue to penetrate the industrial marketplace only if these issues are addressed with customers, if the customers' needs are understood, and if emphasis placed on the advantages of fiber sensors to fill those needs.

Also keep in mind that strain gauge and piezoelectric-based electronic sensors have evolved to where they are today over a period of 40 years. In comparison, the technological base for fiber sensors stands currently at about 15 years.

Application of Fiber Optic Thermometry to the Monitoring of Winding Temperatures in Medium and Large Power Transformers

K. A. Wickersheim

Luxtron Corporation

Santa Clara, California 95051

ABSTRACT

Fiberoptic techniques were first used to measure winding temperatures in power transformers more than ten years ago. Recently interest in such measurements to allow predictive loading and enhanced capacity utilization has increased. As a consequence, a new and more cost-effective fiberoptic temperature measurement system based on the fluorescent decay time technique has been developed for transformer use. The features of this system and its possible use in other power industry applications will be presented.

INTRODUCTION

During the late 1970's and early 1980's the Electric Power Research Institute (EPRI) funded several projects aimed at developing a practical "hot spot" sensor which could be used for direct monitoring of winding temperatures in power transformers.[1] During that same period of time Luxtron independently developed its first-generation fluorescence-based fiberoptic thermometry system.[2] In 1981 EPRI funded an evaluation of this early Fluoroptic® thermometer by the General Electric Company as part of an ongoing study of transformer aging.[3] Based on the results of this evaluation it was concluded that, while certain application-specific modifications of the technology would be desirable, the new sensing technology met the general requirements of the transformer application.

Shortly thereafter, General Electric instrumented a large production transformer with the Fluoroptic sensors. As a result of subsequent thermal measurements on this transformer, built for the Public Service Electric and Gas Company of New Jersey, a number of significant observations were made.[4,5] In particular it was noted that the transformer had substantial excess capacity available for emergency use if loading were based on direct winding temperature measurements. Lampe, et al.[6] subsequently reported results obtained from several Swedish transformers instrumented with fiberoptic temperature sensors of a somewhat different design.[7]

Recently, utility interest in direct winding temperature monitoring for emergency or peak loading has increased. As a result, growth in the use of the fiberoptic sensors in transformers is now showing signs of acceleration. In response to this increase in interest, Luxtron has developed, with financial support from PG&E, a simpler, hardier and more cost-effective system for routine, long-term use on both large and medium power transformers. This paper will discuss briefly the lessons learned from the previous transformer installations and the resultant design features of the new transformer monitoring system.

COMPARISON OF MEASUREMENT TECHNIQUES

First it is worth noting the difference between the direct winding temperature monitoring technique made possible by the fiberoptic sensors and the long-standing method normally used for determining winding temperatures in transformers. The standard technique employs a device called a Winding Temperature Indicator (WTI) which is designed to simulate the thermal behavior of the hottest portion of the winding.[1,4] A known fraction of the load current is passed through a resistive element in the WTI. The WTI is located in the bulk oil at a point remote from the high voltage regions of the transformer. The resistive element is in thermal contact with the oil. The indicated rise in temperature of the element relative to that of the oil is calibrated to mimic the rise in the actual winding temperature.

While this technique is very widely used, it has obvious deficiencies. First, the accuracy of the simulation depends on the correctness of the model used. Further, because the WTI does not measure the actual winding temperature, any unanticipated problem, such as might be caused for example by an obstructed oil duct, will go undetected. Clearly a direct measurement of winding temperature is to be preferred if critical loading decisions are to be made based on the thermal data. Fiberoptic thermometry techniques continue to provide the most practical solution to this need.

The Luxtron technology used in most of the U.S. installations from 1984 to the present time utilizes the measurement of the fluorescent decay time of a hardy inorganic photoluminescent sensor material (manganese-activated magnesium fluorogermanate) to determine the sensor temperature.[8,9] The instruments, which provide pulses of blue light from a Xenon flash lamp to power the phosphor sensors, and which detect and interpret the returning fluorescence in terms of sensor temperature, are all multi-channel systems capable of continuously monitoring from four to twelve sensors simultaneously. The fibers used internal to the transformer are of all-silica construction (a high purity silica core surrounded by a doped-silica cladding) and are therefore totally immune to the effects of prolonged exposure to hot transformer oil on fiber transmission. Special installation hardware, including hardy all-plastic underoil connectors which can be used in the high field regions near the windings and convenient connectorized tank wall penetrators, has been developed to minimize the amount of fiber which must be handled during transformer manufacture and to simplify final assembly of the optical system.

A major virtue of the Luxtron decay time technology, relative to all other known fiberoptic technologies, is that the measurement is of a well-characterized, intensity-independent property of the sensor material. The system therefore behaves much like a thermocouple system where measurements of acceptable accuracy can be made immediately upon connecting an instrument to the sensor without need for calibration. This allows the winding sensors to be pre-installed during transformer manufacture and an instrument to be connected and used reliably at a later time. Since the sensors are totally passive in nature and made from extremely hardy and stable materials, reliable measurements can be made at any time during the life of the transformer as long as the optical path (fiber) remains intact.

USE OF FIBEROPTIC SENSORS IN TRANSFORMERS

After ten years of trial use, the fiberoptic techniques are still not used routinely in transformers. However there have been a significant number of transformer installations during this time period and these installations have demonstrated both the practicality of the technology and the value of the information obtainable by means of direct measurements as compared with the WTI approach. Most installations to date have been for purposes of establishing or improving the thermal behavior of new transformer designs, for troubleshooting and for monitoring of corrected thermal problems, and for quantifying the capacity of transformers which have been rebuilt using high temperature insulation materials.

Recently a Dutch transformer manufacturer, Smit of Nymegen, has begun using the Luxtron fiberoptic sensors in its own factory testing of large transformers.[10] This manufacturer is also willing to leave the sensors in place for use by the utility customer if the customer so desires. This is significant since most transformer manufacturers have tended to resist installing the new sensors.

The Pacific Gas and Electric Company (PG&E) has installed sensors in a number of transformers over the past few years, initially during the rebuilding of selected transformers and more recently by field retrofit. PG&E's primary reason for undertaking this program is to explore the possibility, using direct measurement, of predicting in advance the ability of its transformers to survive peak overloads without requiring back up equipment. This procedure allows temporary capacity enhancement and thereby defers the addition of new equipment. This program is significant for two reasons: (1) it provides a clear method of establishing the value of the direct winding temperature measurement system and (2) it could lead to other field retrofit programs. Only by field retrofit could significant numbers of transformers be instrumented with sensors in a reasonable period of time.

The points just raised suggest the possible development of a major transformer market for the fiberoptic technology. Many factors, including industry inertia, manufacturer resistance, the higher cost of the new technology and a general lack of utility awareness of the need to replace the WTI have contributed to the slow rate of acceptance to date. The in-house use by Smit, combined with that company's willingness to provide the installed sensors to customers, is helping to provide a broader base of utility awareness and also to encourage more competitive pricing of sensor installations by other transformer manufacturers. The predictive loading and capacity enhancement efforts of PG&E are also increasing utility awareness, at least in the United States, and are providing a significant motivation for use of the fiberoptic technology.

Ultimately, acceptance for routine use will be based on the utilities' judgment of cost versus value. Extending the capacity of installed equipment safely during peak loading has a very clear payoff in terms of deferred procurement of additional equipment. Cost reduction of the instrumentation is the responsibility of the sensor manufacturer. The next Section will discuss Luxtron's efforts in this regard.

RECENT TECHNICAL DEVELOPMENTS

Optical Fibers and Cables

It was concluded in the earliest installations[3,4,5] that plastic clad silica (PCS) fibers should not be used because the hot transformer oil permeates the fiber jacket and is absorbed by the cladding. This raises the index of refraction of the cladding and reduces fiber transmission. Further, it produces swelling of the cladding. This swelling splits the relatively thin buffer layer and, on occasion, the fiber jacket as well, thus causing instability of the fiber cable configuration. Even if the fibers were jacketed with less permeable materials, the fiber ends would be vulnerable to the introduction of oil and this would prevent the use of any underoil connections. By utilizing all-silica fibers these problems have been eliminated.

Sensor Mounting Techniques

The sensor can be placed in thermal contact with the winding in a variety of ways. Very early installations, carried out before the availability of underoil connectors, utilized Nylon tubing to guide the sensor to its intended location after the transformer was essentially complete. While this technique worked adequately for the early experiments, it has obvious problems. First, dimensions must be known very precisely if the sensor is to move through the tube and into the intended location adjacent to the conductor under the insulation. If the sensor is withdrawn slightly back into the tube, thermal contact with the conductor will become poor leading to inaccurate measurements. Such sensor motion can occur by virtue of vibration or expansion of the tubing relative to the fiber. Also, if the tubing is accidentally kinked or flattened during transformer assembly, it may not be possible to insert the sensor later all the way to the end of the tubing. For these reasons the use of such tubing guides is not recommended.

The sensor can be taped directly to the conductor using the insulating paper which is normally wrapped around the conductor. This gives good thermal contact of the sensor with the conductor and rapid response of the sensor to changes in local temperature. However sensor placement must be done carefully so as not to damage the insulation. The sensor needs to be placed along the side of the conductor in a position where it cannot be crushed accidentally by an adjacent conductor. The sensors used by Smit are installed in this manner.

Last but not least, the sensor can be implanted in a horizontal spacer of the type designed to hold the conductors apart in the assembled transformer so as to leave space for oil flow. The spacer technique allows convenient placement and also provides crush protection for the fiber probes. Tests at EHV Weidmann have shown no fiber damage at pressures on the spacer of up to 3000 psi.[11]

The only disadvantage of the spacer mounting is that thermal response is slowed by the added insulation between the sensor and the winding. It has been shown however by Weidmann[11] that, if the sensor is located within the spacer directly between two adjacent winding disks or turns, its equilibrium temperature will be that of the conductor. With a rapidly changing load, however, the sensor will lag the winding temperatures by as much as several minutes.[12] To date, most Luxtron sensors have been mounted in NOMEX spacers custom fabricated by EHV Weidmann. However, very recently PG&E has experimented with a soft expandable spacer for use in retrofit situations.[13]

Installation Hardware

Three user-specified lengths of fiber are provided, one a pigtail from the sensor to the exterior of the winding, another forming an extension, preferably protected by insulation tubing guides, running from the end of the pigtail to the tank wall, and a third extension running from the outer tank wall to the instrument. All fibers are cabled for added strength, the outer jacket of the underoil fibers being perforated along their lengths to allow rapid oil filling of the Kevlar space subsequent to vacuum bake-out. The internal (underoil) fiber extension is connected to the tank wall penetrator after the winding assembly has been lowered into the tank prior to vacuum bake-out and oil filling. An all-plastic underoil connector of custom design, is used at the high voltage (winding) end. This connector is made of glass-filled Ryton® and is injection molded to provide the desired tolerances and produce parts which are extremely stable over long time periods at high temperatures underoil. Ryton is dielectrically acceptable for use in the high field strength regions.

Tank wall penetrators, which have tapered pipe threads and are designed to be screwed into pre-drilled holes in an adaptor plate designed to be welded to the tank wall, are also provided for each sensor. The penetrator is made of stainless steel and in the most recent design accepts fibers equipped with SMA connectors. The inner and outer fiber extensions are coupled together by connecting them to opposite sides of the tank wall penetrator. The oil seal is made by tightening a jam nut carried by the inner fiber. This forces a flexible Teflon seal against the barrel of the inner SMA connector. An outer cover protects the fibers and connectors at their point of attachment to the mounting plate.

Instrumentation

The Luxtron instrument most frequently used to date is the 4-channel Model 750 (more recently the improved Model 755) although larger instruments (e.g., the 12-channel Model 950) have sometimes been used when more than four sensors were monitored simultaneously. The Model 750 was designed for laboratory use. Over the past few years the instrument has been modified in various ways to make it hardier and more versatile for use in the transformer application. However, if the fiberoptic technology is to be used more routinely in the future, and in particular on smaller transformers, a new and more cost-effective instrument needs to be developed for field use. Fortunately, recent developments at Luxtron have led to a very small, board level electro-optics package. The new transformer instrument, called the WTS-11, utilizes this recently available technology. The WTS-11 is designed specifically for use on transformers in the field. Its features are based on the accumulation of the past 10 years of transformer experience.