Monitoring of Power Transformer Winding Temperature
Using Robust Fiber Optic Sensing System

ABSTRACT

Direct measurement of actual transformer winding temperature using fiber optic thermometry has been increasing since the mid-1980s due to the growing need to accurately monitor the power transformer hot spot, predict load levels, and improve capacity utilization. While early fiber optic instruments and probes were delicate, resulting in unacceptably high failure rates, the development over the past decade of improved, ruggedized probe designs, in particular, have greatly reduced the likelihood of fiber damage during installation and enhanced the ease of installation. In addition, nearly twenty years of operation on hundreds of transformers deployed in the field, have demonstrated both the industrial robustness of the technology and the value to be gained from direct measurement of the hot spot temperature. This paper will discuss the current state-of-the art in systems and rugged probe design.

WHY DIRECT HOT SPOT MONITORING OF TRANSFORMERS

For many metropolitan utilities, the advent of deregulation and the increasing environmental opposition to construction of new high voltage power lines has greatly taxed the existing transmission and distribution (T&D) infrastructure. The key to being able to balance fluctuations in power load and demand against increasingly tight capacity in the T&D infrastructure often rests in the ability of the utility to make intelligent decisions about transformer loading. This in turn is highly dependent on knowing both the location and winding temperature of the transformer's hot spot.

The conventional winding temperature indicator (WTI), still widely used in the industry, is designed to simulate the thermal behavior of the hottest portion of the winding. This is done by passing a known portion of the load current through a resistive element in the indicator, which is located at a point remote from the high voltage regions of the transformer in the bulk oil (1,2). Unfortunately, it has been proven that thermal modeling can result in large discrepancies between the simulated data and the true winding temperature, as well as a time delay of four to five hours. While perhaps acceptable for normal loading conditions, this can result in serious damage to the transformer or degradation of lifetime, when the transformer is operated at closer to peak rated or even over peak rated conditions, sometimes required in an emergency.

To overcome this limitation, in the early 1980's EPRI became interested in directly measuring and monitoring hot spot temperature of transformer windings and funded a project to evaluate Luxtron's first generation Fluoroptic® thermometer. General Electric Company performed the evaluation as part of an ongoing study of transformer aging (3). Based on the results of this evaluation it was concluded that the fiber optic sensing technology met the general requirements of the transformer application, although certain improvements were still required for reliable long term monitoring. The data indicated that the transformer had substantial excess capacity available for emergency use if loading were based on direct winding temperature measurement(4).

EVOLUTION OF RUGGEDIZED FIBER OPTIC HOT SPOT MONITORING SYSTEMS

In the mid-1980's, Luxtron developed a second generation fiber optic thermometry system(5) that addressed many of the issues encountered in the field with the first generation product. While significant improvement was made in the area of long-term reliability, the high cost and the need to replace key components in the system (e.g. the light source) over the normal life of the transformer, were still considered unacceptable by many users.

In the early 1990's, Luxtron developed a more robust, lower cost, third generation system (WTS-11). Most notably, this system replaced the limited life halogen flash lamp light source with long life LEDs. In addition, a new ruggedized probe, designed specifically to minimize breakage during installation was developed.

In 2001, in response to feedback from key utilities, Luxtron developed a fourth generation system (WTS-22). In addition to the ability to monitor temperature, this fourth generation system has built-in control capability to allow automated control of relays and pumps.

One indication of the progress made in the development of industrially robust fiber optic hot spot monitoring systems, is the 10-year warranty carried by the fourth generation WTS-22.

FIBER OPTIC HOT SPOT MONITORING TECHNOLOGY

The Luxtron Fluoroptic® technology measures the decay time of a inorganic (ceramic) photoluminescent sensor material (i.e. a "phosphor"). The phosphor sensor is attached to the end of a quartz fiber, which is cabled with Teflon sheath to ensure high dielectric integrity. The sensor is subjected to excitation by a light pulse, generated by a high intensity LED at the appropriate wavelength, which produces hundred of pulses per second.

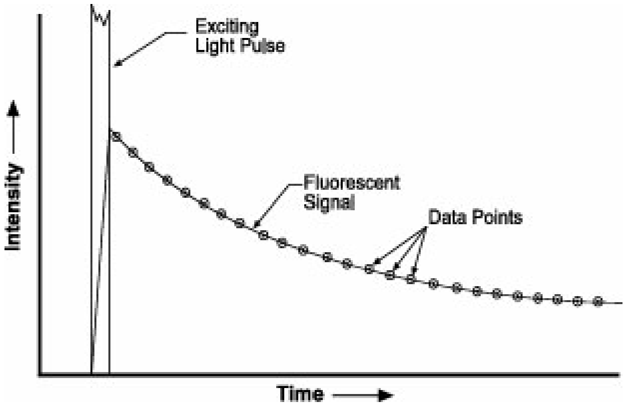

Figure 1 Plot representation of method for extracting decay time

The measured temperature is a time domain, intensity independent, property of the phosphor. The samples are averaged and curve fitted for the calculation of decay time (Figure 1). The decay time of the phosphor changes predictably and repeatably with change in temperature of the sensor. A calibration table correlates the measured decay time to temperature (Figure 2).

Because the measurement is an ***intensity independent, inherently stable*** property of the phosphor, this makes Luxtron's Fluoroptic® technology particularly well suited to industrial transformer applications vs. alternative fiber optic technologies (e.g. semiconductor adsorption-edge, Fabry-Perot) on several dimensions:

No calibration or long-term drift: Fluoroptic® systems are not subject to long term drift and therefore do not require periodic calibration. This is a major virtue when applied to hot spot monitoring systems mounted on transformers that are often found in isolated geographic locations. Also, since the sensors are passive in nature, reliable measurements can be made at any time during the life of the transformer as long as the fiber remains intact. Other technologies are intensity dependent; calibration shift can occur as the light source ages.

Sensors independent of instrument: Fluoroptic® probes can be mixed and matched with different instruments and still achieve high precision measurements. This allows the winding sensors to be pre-installed during transformer construction and an instrument to be connected at a later time. Other technologies require probes and instruments to be calibrated together to achieve a comparable degree of precision.

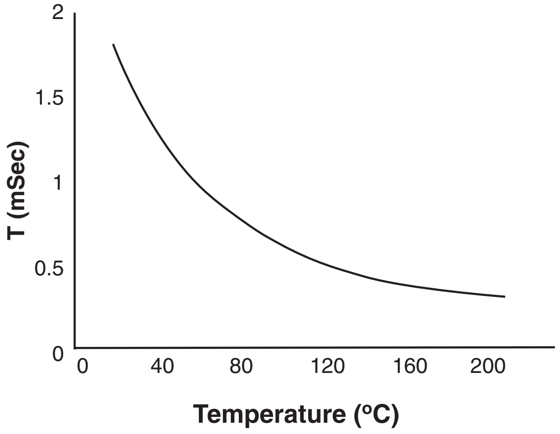

Figure 2 Calibration table correlating decay time to temperature

Ability to use long life light sources: Fluoroptic® systems use LED light sources designed for industrial applications with its virtually unlimited life. Other fiber optic technologies require the use of a broadband light source such as an incandescent or halogen light bulb that have typical lifetime ratings of 1½ years. Replacing a light bulb in the field can be problematic given the geographically isolated location of many transformers. Also, replacing a light bulb requires proper remounting in the optical assembly and recalibration with sophisticated photometric equipment, normally necessitating return of the instrument to the manufacturer.

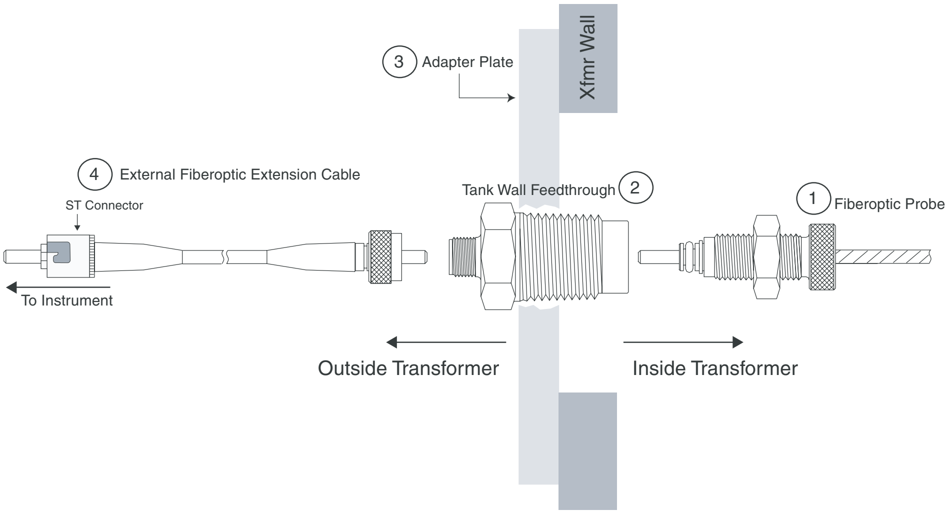

Figure 3 Fiber optic hardware assembly, from probe to outdoor extension cable.

The probe tip is generally attached to the transformer winding via a horizontal spacer. Probes can be of variable lengths (most commonly 4 and 6 meters) depending on the sensor location and the size of the transformer. The other end of the probe fiber is routed to a tank wall feed-through connector. An outdoor extension cable is connected to the other side of the feed-through, which carries the signal from the probe to the instrument where the data are processed (Figure 3). The instrument may have multiple channels. A standard unit consists of 1 to 4 channels. Measurements from all channels can be updated simultaneousl.

RUGGEDIZED PROBE DESIGN

The probe consists of a small sensor tip about 1 mm in diameter, as shown in figure 4. The tip is adhered to one end of the fiber and encapsulated with a layer of Teflon® FPA. An additional protective Teflon layer is placed over the encapsulation to ensure complete protection of the tip from mechanical and transformer oil damage. The fiber itself is also double-jacketed with Teflon PFA. The outer jacket is perforated along the length of the fiber to allow oil to penetrate into the air space between the out and the inner jacket. The other end of the fiber is terminated with an SMA connector for connection to the feed through at the tanks wall.

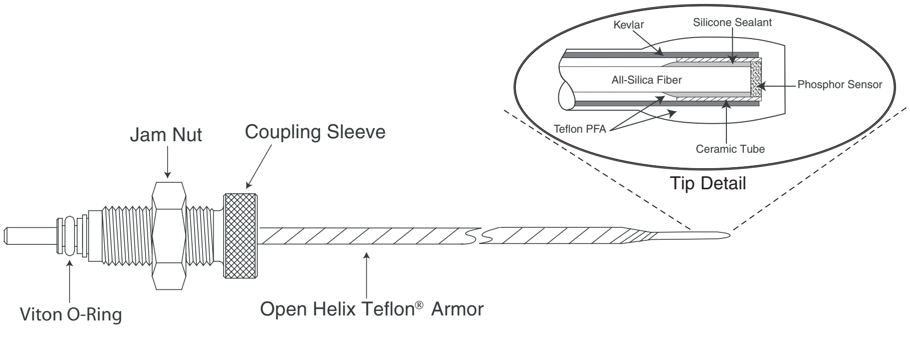

Figure 4 Rugged transformer probe with spiral wrap and probe tip detail

Luxtron worked extensively with transformer manufacturers to improve ease of installation and reduce susceptibility to probe breakage during installation. The most common cause of probe breakage during installation was the fiber being bent too sharply or pulled into a knot. One major improvement made over the past decade has been to increase the flexibility of the fiber by reducing the fiber core size to 200 micrometers. This greatly reduced the incidence of breakage during installation by reducing the fiber bend radius to 2 to 3 millimeters. A second key improvement was to add a white, thick-walled Teflon spiral wrap to the outside of the double Teflon-jacketed probe. This greatly improved the impact resistance of the fiber to tools or heavy equipment being accidentally rolled over it and also prevents the fiber from being bent sharply. The white color also improved visibility.

A drawing of the current ruggedized probe is shown in figure 4. Probes, made with the ruggedized design, have been extensively tested for their improved mechanical strength as well as their retained dielectric strength. The table below summarized the test data of the ruggedized versus non-ruggedized (old) designs.

PROBE TEST DATA

Test	Non-Ruggedized Design	Ruggedized Design
Crush test using dropped weights	Failed @6.8 ft LB	No failure up to 17 ft LB
Knot test using static weights	Failed @ 1 LB	Failed @ 3 LB
Bed test around a mandrel	Failed @ 6-7 mm radius	No failure @ tightest bend radius achievable
High voltage test in oil	No failure up to 143 kv/in	No failure up to 143 kv/in

SENSOR INSTALLATION METHODS

The sensor can be placed in thermal contact with the winding in a variety of ways. The most common technique is to implant the sensor 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. Three types of spacer materials have been used: Nomex, cardboard and Gortex. Tests at EHV Weidmann have shown no fiber damage at pressures of up to 3000 psi(6) using a Nomex spacer. Nylon tubing can also be used to guide the sensor to its intended location after the transformer is complete. The sensor can also be taped to the conductor using the insulating paper, which is wrapped around the conductor.

The tank wall penetrator has tapered pipe threads (see Figure 3). It can be screwed into pre-drilled holes in an adapter plate welded to the tank wall. The penetrator is made of stainless steel and accepts fibers equipped with SMA connectors. The probe and outer fiber extensions are coupled together by connecting them to opposite sides of the tank wall penetrator. Each connection on either side of the tank wall penetrator incorporates a static radial Viton O-ring seal. The precisely machined glands of the seals and the oil resistant Viton provide for an excellent seal. The radial design allows for repeated connection and disconnection of the fiber probes and extension without damaging the O-ring. In the event that a seal does degrade over time, this redundant seal design allows the outside O-ring to be replaced without having to open the transformer. The dimensions of the connectors and penetrator have been increased for easier handling even when gloves are used. A knurled nut instead of a hexagonal nut is used to prevent possible over tightening of the jam nut, causing permanent deformation of the seals. The spacing among the penetrators is increased to make proper connections easier to achieve. An outer cover is available to protect the fibers and connectors at the mounting plate.

INSTRUMENTS

The current fourth generation (WTS-22) instruments are designed in modular form. The optics, data processing and communication electronics for each channel are protected inside a DIN rail mounted plastic box. The instrument can be equipped with from one to four channels and housed in a standard wall/panel-mount or rack-mount or in a NEMA 4 box (Figure 5), the latter of which can be mounted on or adjacent to the transformer. The rack mount version is provided for incorporation within a SCADA enclosure.

Figure 5 Rack mount and optional NEMA -4 boxed WTS-22 instruments

The system provides temperature measurement resolution of 1.0 °C over a range of -30 °C to +200 °C. The accuracy is ±2 °C without calibration. The unit is capable of operating in environments ranging from -30 °C to +65 °C ambient temperature and 95% relative humidity (non-condensing). The system is fully surge-protected to 3000V per IEEE C37.90.1-1989.

Temperature outputs, threshold alarm signals, and system diagnostics can be sent to the utility's SCADA system. Normal data rate is one reading every 10 seconds.

SUMMARY

Fiber optic direct winding temperature sensing systems, based on Luxtron Fluoroptic® technology, have evolved considerably since their introduction in the early eighties from laboratory instruments to robust, industrial control systems. Experience gained by working directly with both utilities and transformer manufacturers have led to the development of today's robust fourth generation systems and ruggedized probes. The intensity independent nature inherent in the Fluoroptic® temperature measurement technology, versus other fiber optic technologies, makes these systems ideally suited for use with transformers in geographically isolated locations.

Nearly twenty years of operation on hundreds of transformers deployed in the field, have demonstrated both the industrial robustness of the technology and the value to be gained from direct measurement of the hot spot temperature.

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