

# OPTIMUM TRANSFORMER COOLING CONTROL WITH FIBER OPTIC TEMPERATURE SENSORS

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## Abstract

Cooling control of power transformers is traditionally provided by a winding temperature indicator (WTI) that is based on a measurement of the top-oil temperature and a simulation of the winding hottest spot temperature. This method has some drawbacks and utilities are now considering the application of fiber optic temperature sensors for this critical function.

Assessing the winding temperature from directly measured top oil temperature can lead to significant errors depending on the cooling mode and the shape of load profile. This situation is reflected in the current revision of the IEEE Loading Guide. The industry consensus leans toward a method based on the bottom oil temperature and a proper representation of the temperature evolution in the cooling duct.

The various hot spot temperature calculation methods are reviewed for the actual case of a 240MVA transformer where fiber optic sensors have been selected for the control of the cooling banks. It is shown that in case of rapid load change, the methods used by classic WTI can indicate a lower temperature by more than 10°C even if they are properly adjusted for the steady state conditions. It appears that with the dependability of modern fiber optic sensors, the long-term performance of transformer cooling can be better achieved with these more accurate monitoring devices.

## 1 Winding temperature determination

Winding temperature is a prime concern for transformer operators. This variable needs to be known under any and all loading conditions especially the unusual condition involving rapid dynamic load changes. Accurate knowledge of the winding hottest spot temperature is a critical input for calculation of the insulation aging, assessment of the risk of bubble evolution and short term forecasting of the overload capability. It is also critical for efficient control of the cooling banks to insure that they can be set in motion quickly when needed.

Today, several methods are available for on-line determination of the winding hottest spot temperature.

### 1.1 WTI approach

Cooling control of power transformers is traditionally provided by a winding temperature indicator (WTI). These devices typically rely on a measurement of the top-oil temperature and a simulation of the winding hottest spot temperature rise. This method has drawbacks and many utilities are now considering the application of fiber optic temperature sensor for this critical function; some of these utilities have recently used the fiber optic sensors to control the cooling banks to insure that they can be set in motion quickly when needed.

WTI's come in several variations. The classical instrument involves a bulb inserted in a thermowell and surrounded by insulating oil. To simulate the winding temperature, the thermowell is additionally fitted with a heater element, fed by a current proportional to the transformer loading. The bulb is filled with a gas or liquid with a large coefficient of thermal expansion. It is connected through a capillary tube to a spiral wound Bourdon tube in the measurement device. The Bourdon tube will unwind slightly when the gas expands in response to increasing temperature and the torque generated is transmitted to a pointer moving in front of a calibrated scale.

In some variations, the heating element is located directly in the measuring instrument. In more recent devices, the top oil temperature and load current signals are fed to a numerical microprocessor where the winding hot spot temperature is calculated using a standard algorithm based on inputs from the top oil temperature plus an increment for winding hot spot rise.

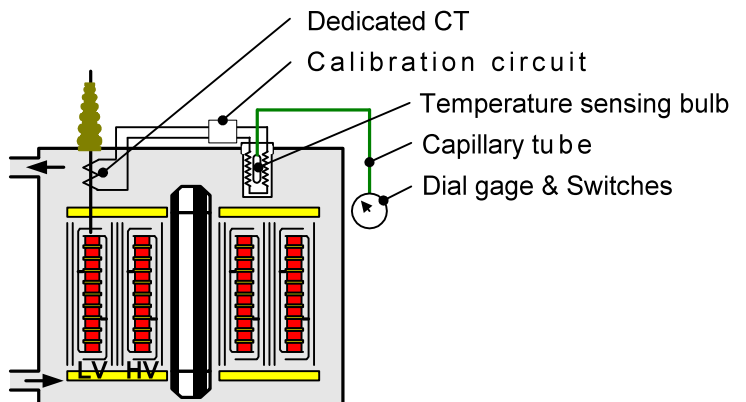
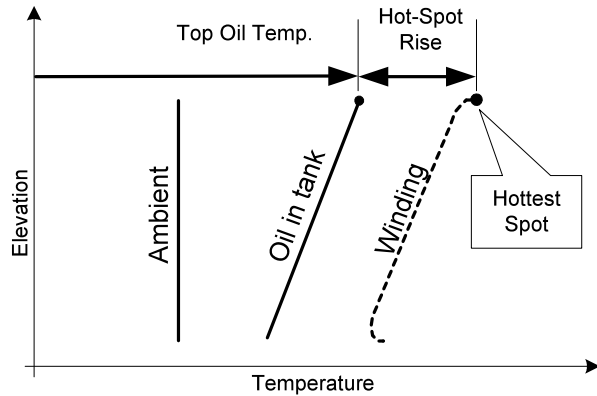


Fig.1 Schematic arrangement of WTI.

This simulation method is consistent with the traditional equation used in loading guides since 1945. It implies that the winding hot spot temperature can be continuously simulated (or calculated) by measurement of the top oil temperature plus a factor proportional to the load, as follows:



$$\Theta_{HS} = \Theta_{TO} + \Delta\Theta_{HR} * K^{2m}$$

Where:

- $\Theta_{HS}$  is the winding hot spot temperature
- $\Theta_{TO}$  is the top oil temperature
- $\Delta\Theta_{HR}$  is the hot spot rise at rated load
- $K$  is the load factor in per unit
- $m$  is the winding exponent (usually near 1)

Fig. 2 Hot spot temperature computation using top oil temperature.

This calculation method is based on the thermal diagram shown in Figure 2. It assumes that the temperature of oil at the top of cooling duct is the same as the top oil temperature measured in an oil-filled thermowell near the top of the tank.

The rated winding hot spot rise above top oil is usually derived from the temperature difference between average winding and average oil temperature; this difference is then multiplied by a hot spot factor to take account of additional losses toward the ends of the winding. This hot spot factor is normally estimated using factory heat run test results and has to be provided by the manufacturer. For a given load current, the difference between average winding and average oil temperature is assumed to remain the same, operating under any cooling stage. This method was the basis of IEEE and IEC loading guides since 1945 and has been well accepted by the industry ever since.

Now that transformers are used closer to their rated values and overloading is more frequent, it has been recognized that the hot spot calculation method needed improvement to cover occurrence of a step load increase. It was observed that the model was not adequate to simulate the winding temperature during severe dynamic loading conditions, because:

- Oil temperature in the winding cooling duct can be much higher than the top oil temperature
- The time constant of oil in the cooling duct is much shorter than the top oil time constant
- Under sudden load variations, the oil circulation does not respond immediately.

Due to the above factors, the winding temperature transient value can thus be significantly underestimated.

## 1.2 Modeling based on bottom oil temperature

It appears that much better results can be obtained when the calculation is based on bottom oil temperature and oil duct temperature:

$$\Theta_{HS} = \Theta_{BO} + \Delta\Theta_{WO/BO} + \Delta\Theta_{HS/WO}$$

Where:

- $\Theta_{HS}$  is the winding hot spot temperature
- $\Theta_{BO}$  is the bottom oil temperature
- $\Delta\Theta_{WO/BO}$  is the temperature rise in the cooling duct
- $\Delta\Theta_{HS/WO}$  is the winding hottest spot temperature rise over oil near the hottest-spot location

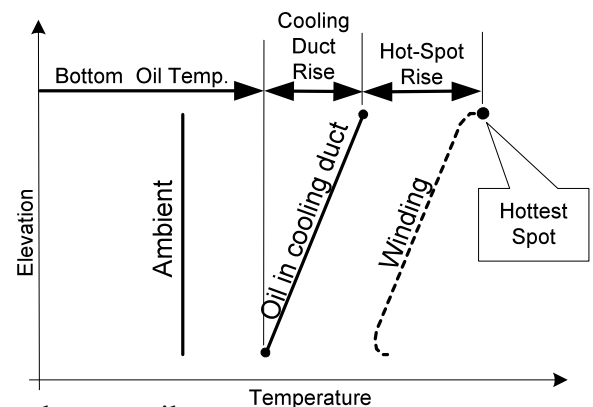


Fig. 3 Hot spot temperature computation based on bottom-oil temperature.

The IEEE loading guide (C57.91) [4], presently under revision, will express a strong preference for the approach based on bottom oil temperature. For the steady state condition, the following rated values are determined for each cooling stage:

losses, bottom oil rise, oil duct rise, and winding rise above oil duct. Equations are also provided for adjustment of these rated values to different tap positions.

Under dynamic loading conditions, the winding hottest-spot rise and oil temperature rise are obtained from conservation of energy equations. This system of equations constitutes a transient forward-marching finite-difference calculation procedure. Losses and temperature rise quantities are adjusted by taking into account the changes in winding resistance and the oil viscosity with temperature.

In order to perform this calculation, the following information is needed for each cooling stage under consideration:

- Top-oil temperature rise over ambient temperature at rated load
- Bottom-oil temperature rise over ambient temperature at rated load
- Average conductor temperature rise over ambient temperature at rated load
- Calculated winding hottest spot temperature rise over ambient temperature at rated load
- Confirmation of oil flow design (that is, directed or non-directed)
- Load losses at rated load
- No-load (core) loss
- Total losses at rated load
- Winding resistances
- Weight of core and coil assembly
- Weight of tank and fittings
- Volume of oil in the tank and cooling equipment.

More precise calculations of loading capability may be performed if the following additional information is available:

- Load losses at rated load at rated tap and tap extremes or all possible tap connection combinations
- Winding resistance at tap extremes or all possible tap combinations
- Total stray and eddy losses as a percent of total load losses and estimated stray and eddy losses
- Per unit eddy losses at hot spot location
- Per unit winding height to hot spot location.

It is possible that in the future this method can be incorporated in a computing device that would provide on-line assessment of the winding hot spot temperature even under transient loading conditions but several difficulties still need to be resolved.

### **1.3 Direct measurement of winding temperature**

Fiber optic (FO) temperature sensing can be seen as a third approach for the determination of winding hot spot temperature under dynamic loading conditions. The use of fiber optic sensors removes several uncertainties in the process of winding hot spot temperature determination, including:

- Calculation of eddy losses and stray losses in the hot spot area
- Estimation of oil flow in the hot spot area
- Estimation of oil temperature in hot spot area
- Estimation of winding temperature rise above local oil in hot spot area
- Adjustment of these values for various tap positions
- Adjustment of these values for various cooling stages
- Modeling of winding(s) time constant(s)
- Modeling of top oil (or top of cooling duct) time constant as a function of oil viscosity.

The main constraints with fiber optic sensors are that they must be installed at the winding manufacturing stage and the locations of the hottest spots must be known to the manufacturer. However this last requirement also applies to the other methods since determination of winding hot spot rise above oil implies that the location of this hottest spot is known.

Assessment of winding insulation temperature under any loading condition is a critical step for efficient management of a power transformer. The traditional model used for hot spot temperature determination has shown serious limitations, especially under transient conditions. New models based on bottom oil temperature could provide more accurate results but they require that 12 to 15 parameters be determined accurately for each cooling stage.

Direct measurement with fiber optic temperature sensors bypasses these difficulties and uncertainties. These sensors provide dependable information for each winding, under any loading condition and they are sufficiently rugged now to provide cooling control during the entire transformer life.

## 2 Field experience with direct temperature measurement

The Priest Rapids Project is located on the Columbia River in Washington State and is operated by the Grant County Public Utility District (GCPUD). The generating station is in the process of being refurbished with new GSU transformers, 240 MVA, 13.2/13.2/230kV, with ONAN/ONAF cooling (Figure 4).

The transformers are located on a concrete powerhouse deck that is aligned NE to SW, exposing the transformers to solar heat during most of the day. The ambient temperature can get fairly high in summer when the power delivery is most critical, and the concrete structure retains heat long after direct exposure to the sun. Since each increase of 7°C in the winding temperature doubles the solid insulation aging rate, Fiber Optic Temperature Sensors were selected for cooling control. They provide the most dependable tool to optimize cooling control and also allow accurate, long term estimation of the insulation aging.

The new GSUs have dual-primaries. In the coil assembly, the two LV 13.2 kV windings are erected one above the other as shown in Figure 5a, as “X” and “Y”. Each unit was fitted with 18 fiber optic sensors in the winding plus three more on the core legs (not shown here).

The winding sensors are located as shown below:

- 6 near the top of HV winding in the spacers between disks or in the oil duct
- 6 near the top of upper primary oil duct (X winding)
- 6 near the bottom of lower primary oil duct (Y winding)



Fig. 4 Application of FO sensor for cooling control on a 240 MVA transformer at GCPUD.

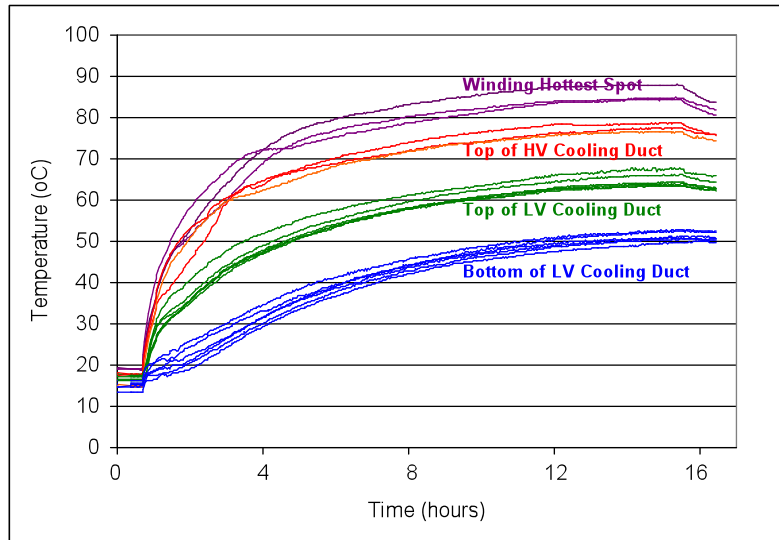
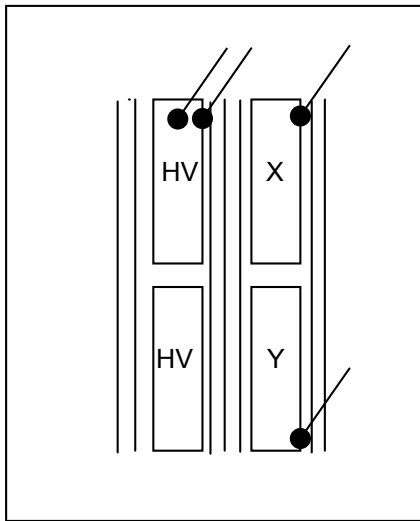


Fig. 5 Detailed locations of fiber optic sensors on the HV and LV windings (5a) and temperature recorded during heat run test under ONAN condition (5b).

The data collected during one ONAN heat run test with constant losses is shown in Figure 5b. All 18 sensors operated normally and measurements are very consistent. Fiber optic sensors on similar locations on phase A, B and C give almost identical results indicating a uniform oil circulation in each phase. The differences between phases may be attributable to oil-flow patterns influenced by the asymmetrical tank geometry – the no-load tap-changer compartment shares the oil space on one end of the transformer – and the influence of the many leads routed to the NLTC.

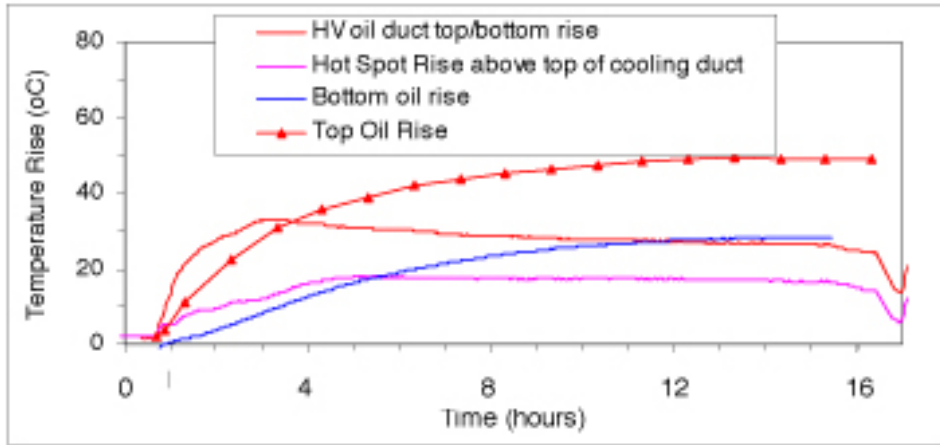


Fig. 6 Temperature rise for various components of thermal model.

Observation of these temperature variations under a steady load condition allows drawing a better picture of the thermal behavior:

- Bottom oil temperature and top oil temperature have similar time constants of about 3.5 hours
- Oil ducts display a much shorter time constant, of about 30 minutes.

### 3 Comparison between WTI and FO under sudden load variations

Results from the normal heat run can be used to define a top oil model that will be the cornerstone of WTI settings. Additional results from fiber optic temperature sensors can be used to develop a model based on the bottom oil temperature and cooling duct temperature that will be more accurate for rapid load variation conditions. These two results are shown as follows:

<b>Top Oil Model</b>	ONAN
Top oil Rise (°C)	49.6
Top oil Time constant (h)	3.5
Hot spot Rise above top oil (°C)	14.5
Hot spot Rise time constant (h)	0.1

<b>Bottom Oil Model</b>	ONAN
Bottom oil rise at full losses (°C)	28.9
Bottom oil time constant (h)	3.8
Oil duct temperature rise (°C)	26.8
Oil duct time constant (h)	0.4
Hot spot rise above top of duct (°C)	8.4
Hot spot time constant (h)	0.1

Let's assume that the transformer is operating on the ONAN cooling stage, where the rated power is 180MVA. From an initial load of 0.75 per unit, the transformer is requested to carry an overload of 1.5 per unit for 4 hours.

Although both models give the same values for steady state conditions, they behave quite differently under transient conditions. This can be illustrated by a large load variation over a short time period. We can assume that at best, the WTI will match the values predicted by the Top Oil Model. This further assumes that the heating element can match the HV winding time constant of 6 minutes. The value to be expected from the fiber optic sensors can be predicted from the parameters extracted from the heat run test results and applied through the Bottom Oil Model.

We find that the oil in the cooling duct rises rapidly to about 21°C above the top oil temperature (Figure 7a). For the same period, the FO-calculated hot spot temperature is about 15°C higher than what is expected to result from the WTI relying on a top oil temperature model (Figure 7b).

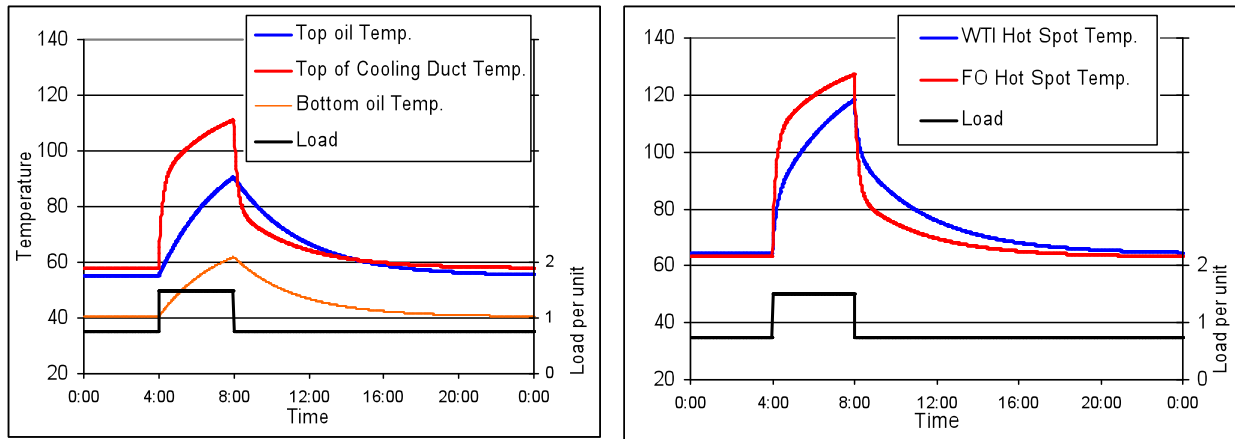


Fig. 7 Comparison of WTI and FO response for a step overload of short duration.

During this 4 hour overload, the transformer would undergo a cumulative aging of 10.7 hours although the aging derived from the WTI would only amount to 3.3 hours, resulting in a significant underestimation of actual life loss.

Now if we consider the case of a cooling control set at 110 degrees, it can be seen that the FO control will initiate the second cooling stage much earlier than the WTI control relying on a top oil temperature model (Figure 8). In this example, the insulation aging accumulated during the overload period is 1.4 hours with FO control compared to 6.4 hours with the WTI control (aging rate is calculated using IEEE equation for thermally upgraded paper). In this case, using FO control instead of WTI control could reduce the actual loss of life by 78%.

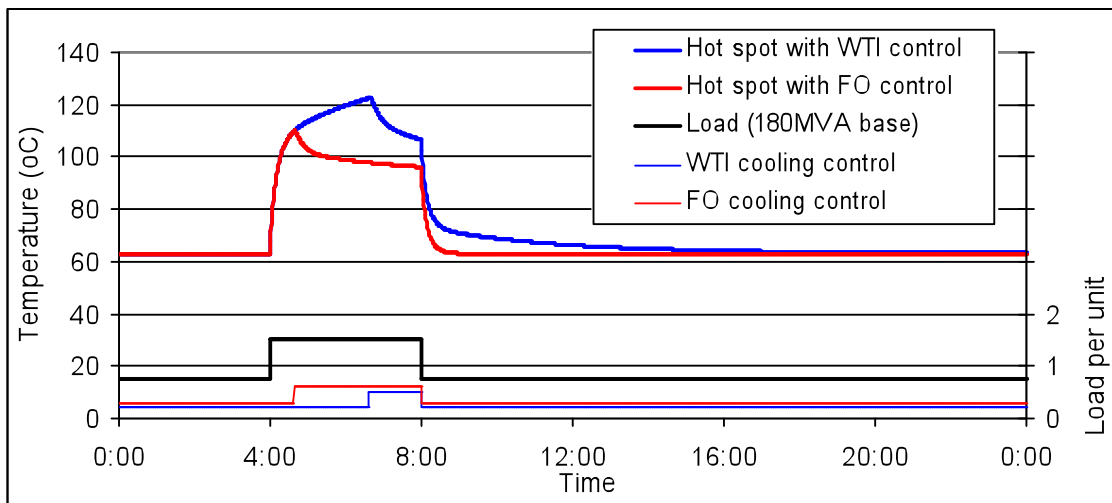


Fig. 8 Comparison of winding hot spot temperature with WTI and FO cooling control.

#### 4 Design requirements for long life fiber optic probes

Making the decision to control the cooling banks using the fiber optic sensors implies that these sensors must be designed to outlast the transformer itself, which normally means periods as long as 50 years or more. When users started to install fiber optic sensors 20 or 25 years ago, they were happy to see them survive the heat run test, as their goal was mostly to confirm the thermal model of their transformers. Today, however, transformer users are demanding much more.

Ideally, long-life probes should have the following characteristics:

- The basic sensing technology must be absolutely stable with time
- The sensing technology must be absolutely stable even in presence of harsh chemical environments, and at elevated temperatures over a very long time
- The probes must be designed so they can mechanically survive the difficult transformer environment, which consists of steady vibrations and frequent thermal cycles

- Furthermore, the sensing technology that converts the light signal into temperature information must be insensitive to light intensity measurement and rely solely on optical features that give temperature readings that are independent from any such light intensity variations. This is required to avoid problematic compensation for any aging effects in the optical fiber link and any interconnections used in this link.

Each one of these essential points is discussed below:

The Neoptix sensing technology relies on the well proven GaAs sensing technology. This technology has been used for temperature sensing inside power transformers for more than 10 years. It is abundantly documented in the open literature. The technology is based on a well known phenomenon that is exhibited by any semiconductor material: the band gap wavelength or absorption shift. As it is a fundamental characteristic of the crystalline structure of the GaAs material, it is always the same and thus never requires calibration or correction that might be provided by probe-specific correction factors. Furthermore, this absorption shift is absolutely stable as a function of time; in a thousand years from now, it will still have the exact same shift!

The band gap wavelength technology has a big advantage of being completely insensitive to signal or light intensity. This means that any aging effects that might happen through the optical link between the electronic module and the GaAs chip has no effect on temperature reading accuracy, and never requires calibration. Also, as temperature reading rates for transformer are relatively slow (e.g. seconds is sufficient, not milliseconds), the Neoptix electronic module can be set to operate with derated light level, which gives extraordinary long term light source lifespan, calculated at more than 300 years for a typical system (more than what can be expected from LEDs).

Neoptix probes are constructed with the GaAs chip being freely mounted at the end of the fiber optic cable (Figure 9, patent pending). Thus, the sensor “floats” in a very small volume of transformer oil. This insures that constant mechanical vibrations inside the transformer and the numerous temperature cycles that the transformer will be subjected to will not “fatigue” the bond between the GaAs chip and the fiber, while also exhibiting virtually no partial discharge.

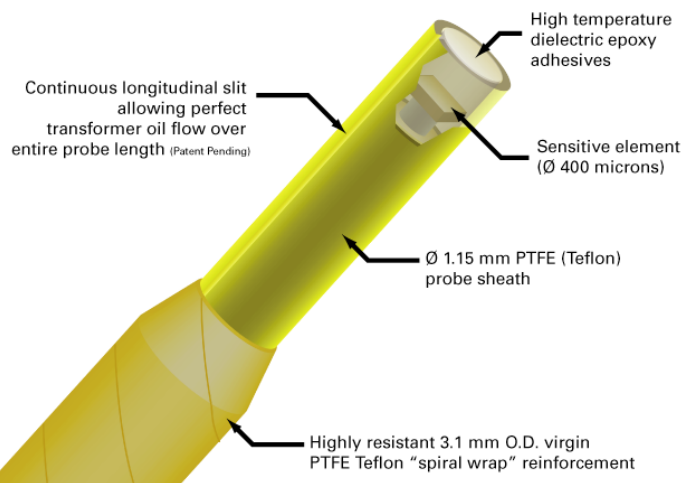


Fig. 9 Detailed construction of a Neoptix fiber optic temperature sensor.

## 5 Recommendations for efficient installation of fiber optic temperature sensors

The 240 MVA transformer studied in this paper has been fitted with a large number of fiber optic probes, i.e., a total of 21 probes. Normally, 4 to 12 probes are considered as being enough, while providing some spares in case of breakage of some probes during installation.

A good discussion of sensor placement is provided in section 4 of the IEEE P1538 Guide for the Determination of Maximum Winding Temperature rise in Liquid Filled Transformers [1].

Typically, 2 probes will be mounted at the hot spot location in each phase. Usually, the conductors near the top of a winding are exposed to the maximum leakage field and the highest surrounding oil temperature; however, experience has shown that the hottest spots are down a few conductor layers from the top. Furthermore, at least one additional probe should be giving the top oil temperature. ALL probes should be monitored during the heat run test, and the hottest ones should be selected for long term monitoring. Depending on the winding design parameters, it is often the case that the highest temperatures are found in the low voltage windings.

Ensure that all probes are solidly attached in their intended position. Teflon® material tends to soften as the temperature increases, so it is important that the probe cable be well supported at the installation point and along its whole length. When routing the probe, spool any surplus cable with a diameter of at least 30cm.

As required, the probe cable should be routed through modified gap spacers. Extra care must be exercised to avoid situations where the cable might be crushed, for instance from compression during assembly of the coil stack, or especially during special conditions such as a short circuit when in operation.

### 5.1 Mountings probes on conductors or in radial spacers

Although it may seem more accurate to mount fiber optic probes directly on the conductors, experience has shown that it is much simpler to mount them in radial spacers, as shown in Figure 10. Also, it appears that the temperature [3] under the spacer is indeed higher by 1 or 2°C than the surrounding conductor. Furthermore, when the probes are installed in spacers, they can be installed much later during the transformer manufacturing cycle, thus further reducing the chances of probe breakage. It is not surprising thus that most fiber optic sensors today are installed in radial spacers.

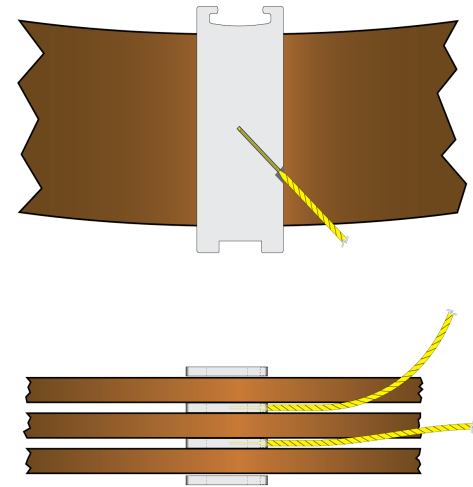


Fig. 10 Probe installation in spacers.

## 6 Conclusion

Numerous papers have shown that older transformer loading equations were quite imprecise. The new equations presented in recent versions of loading guides are quite complex, and assume knowledge about parameters that are not readily available. A large number of assumptions must be made in order to use them. As demonstrated in this paper, the solution that removes most of the guess-work is to use fiber optic sensors embedded into the transformer windings, both for the heat run tests and for the long-term transformer cooling control. That is not to say that conventional control means (WTI, etc.) will disappear any time soon, as progress is being made there too. We expect to see more and more transformers in the future where fiber optic sensors and conventional measuring means will coexist.

FO probes have been installed in transformers for more than a quarter of a century. The technology has advanced enough in the meantime so we can now envision using them to replace the 50 years old WTI device to control the cooling of newly built transformers. Installation procedures for probes have also matured, resulting in an installation success rate approaching 100%.

The Neoptix' FO sensors have been designed to outlast the life of the transformers in which they are installed. Proven GaAs technology never requires recalibration, and probes can now be manufactured such that continuous transformer vibrations and thermal cycles have minimal effects on their expected life span, which should be 50 years and more. By utilizing FO cooling control and the new loading guide methodology, it is possible to minimize the solid insulation aging during operation, thereby reducing the chance of premature equipment failure by this mechanism and making a 50 year or longer transformer lifetime a realistic expectation. Conversely, FO technology can allow utilities to manage overload conditions more effectively, making better-informed economic decisions about trading Megawatts for transformer life.

The installation of 4 new HHI (Hyundai Heavy Industries, Ulsan, Korea) GSU transformers at Priest Rapids Dam, GCPUD (Grant County Public Utility District) in Washington State has shown that the GaAs sensors can be reliably used to control the cooling fans. Some of these transformers have now been controlled by Neoptix T/Guard+ systems for more than 2 years, with no problems reported.

## 7 References

- 1) IEEE P1538-2000 "Guide for Determination of Maximum Winding Temperature Rise in Liquid Filled Transformers".
- 2) IEEE Draft 2006. "Requirements of Winding Temperature Indicators for the Rapid Response and Accurate Measurement of the Hottest Spot Winding Temperature in Liquid Filled Power Transformers".
- 3) Bérubé, Aubin and McDermid. "Transformer Winding Hot Spot Temperature Determination", Electric Energy T&D Magazine, March-April 2007.
- 4) IEEE C57.91 1995 "IEEE Guide for Loading Mineral-Oil-Immersed Transformers".