

## Use of Fiber Optic in Transformers

### **“FIELD EXPERIENCE WITH MULTIPOINT INTERNAL TEMPERATURE MEASUREMENTS OF CONVERTER TRANSFORMERS”**

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#### INTRODUCTION

Thermal stresses in power transformers are determining the life span of the transformer. The most important life limiting component in a transformer is the paper insulation of the windings. The aging rate depends on operating temperature, moisture, oxygen and acidity levels within the oil, and also the type of paper. The primary ageing process is de-polymerisation (DP) of the cellulose polymer chains. As the DP factor becomes lower the mechanical strength of the paper decreases. The remaining life time of the transformer could be determined more precisely by measuring the DP factor.

One of the most important parameters of the transformer is the operating temperature. It has a major influence on the aging of the insulation and on the transformer's lifetime. An accurate prediction of the hotspot in the winding is consequently very important for both manufacturers and end-users as the hotspot will cause degradation of the transformer oil and paper insulation. It is widely accepted that the insulation degradation approximately doubles with each 10°C temperature rise. The insulation degradation caused by overheating is irreversible.

Therefore, it is particularly critical to locate and determine the hot spot temperature accurately. This information mainly comes from the designer of the transformer. The hot spot temperature and its location are determined in the design process and are as accurate as the assumption, by the designer, of the initial conditions. In the every day life, the hot spot temperature and its location are not known, they remain a “design” parameters.

With respect to thermal stresses of the transformer, typically we are provided with the top oil temperature gauge and the winding temperature gauge. Interestingly enough, the winding temperature sensor is not physically in the winding. It is located few feet away from the top oil temperature sensor and it senses the same temperature. However, it is calibrated to add a number of degrees to the temperature. That value would represent the winding temperature. In practice, the values of the top oil temperature and the winding temperature are not read. Instead, the gauges are design to provide alarm and tripping signals if, for any reason, the temperature values should exceed the set values. Practically, there is no knowledge of these temperature readings until alarm or tripping signals are triggered. When such a situation presents itself, we say that the transformer was “cooked”.

#### OVERLOADING

Power transformers have inherently some margin of overloading capability. The rated power of a unit is basically the load level that will result in internal temperatures that are below the limits set forth by standards such as IEEE and IEC. The normal life expectancy is referred as continuous duty under normal ambient temperature and rated operating conditions. Most of the transformers spend all their life under normal service conditions.

But in last decade, many changes in power systems industry have taken place. Deregulation and privatization have created the whole new outlook with respect to maintenance and loading. As a consequence, electricity is now traded as a commodity and the market price becomes a driving force for loading of the power systems.

The overloading of the transformers is introduced, in general, for the following reasons:

- sudden loss of the part of the system resulting in overloading the rest of the system to make up for the demand.
- sudden increase in the demand due to climate conditions like cold spells and heat waves.
- increase in the demand that was not planned for and it was not followed by the increase in the supply capacity.
- market conditions in the game of opportunities i.e. an excellent spot price.

For the above reasons, power transformers are overloaded more often and for longer periods. The equipment in service is being used closer to its limits and its maximum load capacity. This becomes a concern to the system

engineers that need to predict the life expectancy of the transformers and plan for the timely replacements of spare transformers. Sudden failure of one of the critical transformers for which replacement is not available may cause an enormous loss of revenue and inconvenience for customers. It takes a minimum 9 to 18 months to obtain a new transformer. At the other extreme, a low capital cost strategy would be to leave all units in service until failure. A “replace on failure” strategy has the apparent attraction of maximising the utilisation of capital assets, but is made uneconomic because of the need for an unrealistic system with a very high level of redundancy [5].

The application of load in excess of nameplate rating involves a degree of risk and accelerated aging. The probability of occurrence of the gas bubbles is closely related to winding hot spot temperature and moisture content of insulating paper. Bubble evolution from overloading of the transformer is a concern due to possible dielectric failure.

Thermal aging of solid insulation results when overloading for longer periods. With time, the cellulose chains undergo a de-polymerization process and consequently reduce the mechanical strength of paper. Since overloading is inevitable for short periods during peak demands, it is necessary to specify the limits of overloading with respect to winding hot spot temperature which determines bubble evolution.

The risk associated with overloading can be drastically reduced if the transformer’s conditions are closely monitored throughout the overload period. Although thermal loss of life of the winding insulation cannot be prevented, on-line monitoring can provide a dynamic evaluation of insulation degradation. At present, monitoring systems are developed to give a timely warning of imminent failure. These can prevent some catastrophic failures that develop relatively slowly. It is uncertain if they can give any warning for the random system events that trigger many failures.

The detection of hot spot in electrical apparatus in service is not an easy task. A prerequisite for the real hot spot detection in transformer windings is the installation of the optical fiber into the winding. Initially, the application of the optical fiber into the windings has met a lot of reluctance on the part of the utility engineers as well as the transformer manufacturers. However, pressed by the need to know the winding temperature in order to better control the loading of its transformers, Manitoba Hydro decided in 1998 to equip one of the new converter transformers with 48 fiber optic probes. The manufacturer was willing to try to imbed the fiber optic tips on the winding conductor while making the windings and also at many other different locations. The intent with so many temperature probes was to obtain the full picture of the temperature distribution inside the transformer. On the day of service, there were 36 probes working. The myth in the industry about the application of the optical fiber inside transformer is that many probes do not function once transformer is put in service. People also believe that optical fiber could cause the dielectric failure of the transformer by being the path to tracking. The percentage of the probes that work depend exclusively on the way the manufacturer is handling the fiber optic wires. Nowadays, the fiber optic wires are equipped with a protective PTFE jacket. Since 1998, Manitoba Hydro has installed fiber optic temperature probes in more than a dozen critical transformers; each of these transformer containing 8 probes. Since 1994, there have been a number of failures of the converter transformers with the service life between 18 to 23 years [1], [2], [3]. The subsequent dissection of the windings has found, in every single case, that overheating of the portion of the conductor paper was the cause of the failure. It is very probable that thermal breakdown, in a localized spot, led to turn to turn short circuit and eventually developed into the dielectric failures and flashover. The decision was made to implement the on line monitoring of winding temperatures using fiber optic technology.

### INSTALLATION OF FIBER OPTIC PROBES

The installation of fiber optic probes into the windings is definitely an ongoing learning process. By time, the manufacturers are gaining experience how to cope with this new challenge and the improvements are evident.

The rated values for the transformer being equipped with 48 fiber optic temperature probes can be summarized as follows:

- Type: Converter-transformer, ODAF cooling
- Rated power: 107 MVA, single-phase
- Line winding:  $230/\sqrt{3}$  kV, 810 A, grounded Y
- Valve winding:  $127/\sqrt{3}$  kV, 1468 A, Y
- Tertiary: 18.2 kV

The transformer is a directed-flow type, with oil forced directly in the windings. All pumps are continuously in service while the fans on Unifin coolers are set in two stages. One set is hand-operated and was continuously operated during the period reported here. The other set is in automatic mode and is turned on when the winding temperature reaches 50 °C.

As a part of its normal duty, this transformer undergoes significant load variations, as can be seen on Figure 13 for the week of May 27 to June 03, 2003. The load demand fluctuations and the periodic connection of a large synchronous condenser result in a daytime load of typically 0.8 p.u. and night time load of 0.4 p.u. These wide load variations allow for a better evaluation of the dynamic behaviour of the IEEE Guide Winding Hot-Spot Temperature model, based on fiber optic temperature probes measurements.

The photos of the first installation of 48 fiber optic probes in this transformer are shown on the next page. Of these 48 probes, 21 were in the line (AC) winding, 22 in tertiary winding, 2 in the core and 2 on neutral lead and



one in the top oil. Within the windings 12 probes were placed inside the paper insulation of the continuously transposed conductor, 17 were in radial winding spacers, 10 were attached to the radial spacers with the tip of the probe in the radial oil duct and a further 4 probes were similarly arranged but with the tip in the oil exit from the winding. Because of the DC stresses on valve winding it was decided not to place fiber optic probes in this winding. Every converter transformer built after had the fiber optic probes installed in the valve (DC) winding.

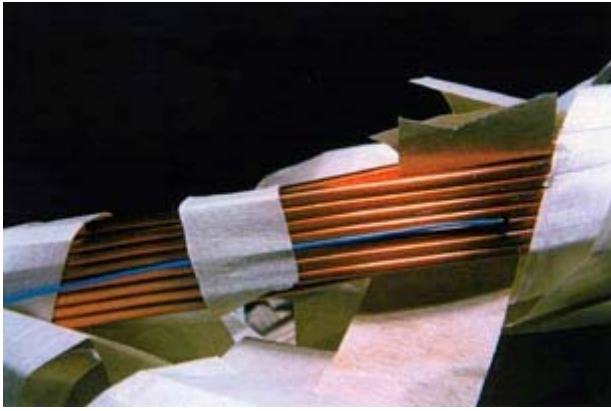
The following photos are used as examples only. The reader is advised to visit Doble web site (<http://www.doble.com>) and review the appendix "I" where all the color photos of fiber optic installation are shown. The photos are self-explanatory and the comments are not included.

**FIGURE1: Converter Transformer, 107 MVA, Single Phase**

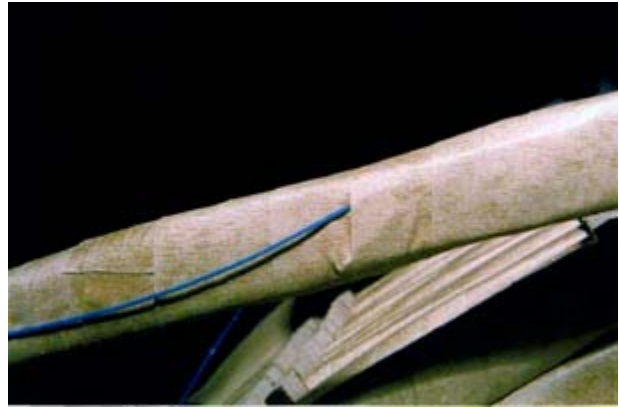
Manitoba Hydro specified 8 fiber optic probes for each converter transformer built since this first installation. In addition, two phase shifting transformers were retrofitted with several fiber optic probes due to known problems of steel plates overheating. On the other occasion the iron core has been slightly damaged during the overseas transport of the transformer. The transformer was conditionally accepted after installing the fiber optic probe in damaged area to monitor the overheating and the warranty was re-negotiated.

The major cause for probe not working was due to handling of the fiber. We suspect that in a majority of cases the glass core was broken by sharp bending. Some probes declared as not-working start to work after the proper cleaning of the optical connectors was done.

The installation of the fiber optic probes in power transformers is certainly challenging, but it can be rewarding either to supervise performance of the critical transformers or to monitor closely the known thermal problems in existing transformers. There are definite benefits in monitoring the winding temperatures. The whole issue about overloading and shortening the life of the transformers will be based on actual measurements. On line monitoring of temperatures and data logging will enable us to analyse the whole range of loading regimes for any time period of interest. The reasonable steps could be taken to manage transformer life more efficiently.



**FIGURE 2: The Probe Tip On The Conductor**



**FIGURE 3: The Probe Tip Covered With Paper**



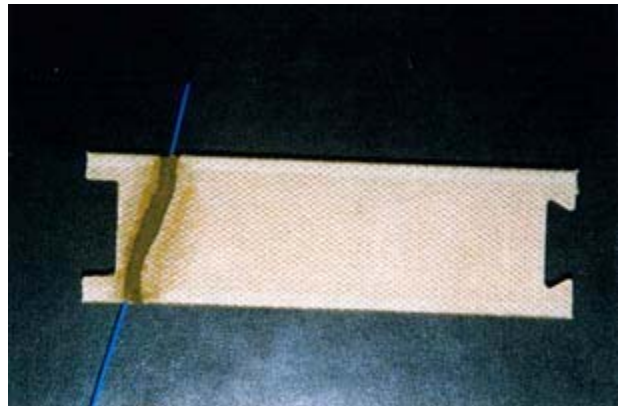
**FIGURE 4: The Probe Tip Fully Covered**



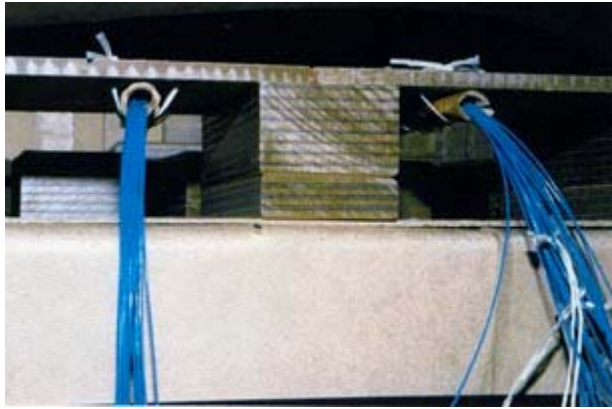
**FIGURE 5: Temporarily Spools During Coil Sizing**



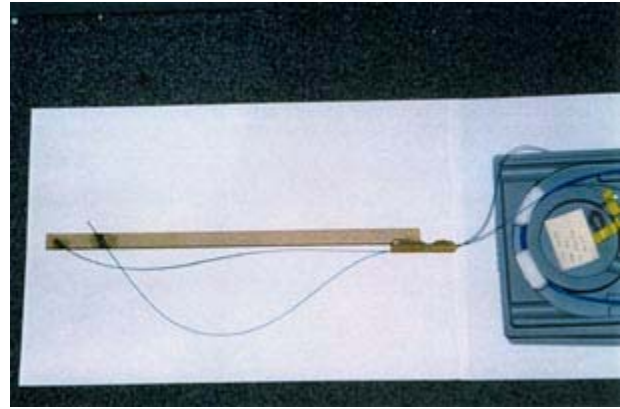
**FIGURE 6: The Key Spacers Cuts**



**FIGURE 7: Probe Secured Using a Glue**



**FIGURE 8: Fiber Optic Exiting Winding**



**FIGURE 9: Core Duct Stick With Probes**

### ON LINE MONITORING AND ANALYSIS

The transformation of the optical signal into an electrical signal is still costly. The expected benefits must overshadow the cost. For this particular reason, we were continuously monitoring only 6 out of 36 probes. These 6 probes were selected as they measure the highest values during the factory load test. The optical connectors interface must be clean; otherwise even fingerprints can prevent the light signal from going through. The instrument for on-line monitoring was a 6-channel data logger shown in Figure 10. The available features are Mega-logger™, Triggered logger and Event logger. The Mega-logger is capable of saving maximum, average and minimum values for every channel for one year. Its analog output module provides connectivity to other monitoring systems. The



remote communication with the unit is also available. The data can be downloaded easily into an Excel spreadsheet format. The trigger and event settings can be used to download the data only after receiving the trigger or event alarms.

Because this was a first time exercise, Manitoba Hydro decided to download the data on a weekly basis to be able to monitor selected locations inside the transformer. The data was collected for a full year to record all four seasons and determine the influence of the ambient temperature. The ambient temperatures were in the range of  $-30^{\circ}\text{C}$  to  $+30^{\circ}\text{C}$  during this observation period. At this point of time, we don't know how to account accurately for the wind chill values in the winter and the humidity values in the summer. These special conditions alter the ambient temperature much more than we actually measure. The ambient temperature input and the loading current input were obtained from another monitoring system on the same transformer. The following figures are intended to show the thermal behavior of the transformer under consideration.

**FIGURE 10: Six Channels Data Logger**

For clarity and to prevent the congestion of traces we considered presenting the monthly plots of line winding temperature and top oil temperature only. The cold month of January 2003 and the hot month of July 2003 are presented. It was mentioned before that transformer undergoes significant load variations. The temperature measurements follow the load exactly.

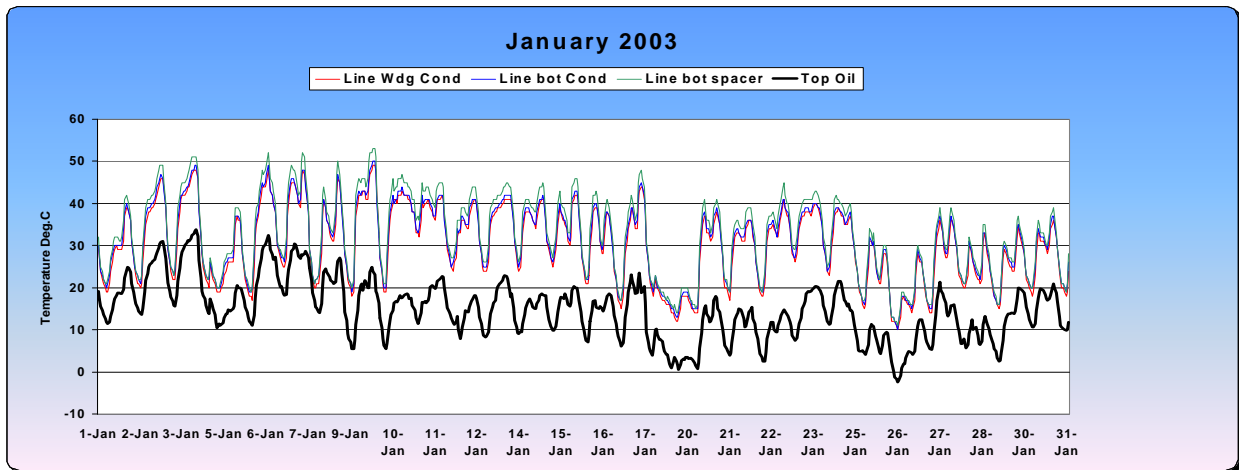


FIGURE 11: Line Winding and Top Oil Temperature Measurements For Month Of January 2003

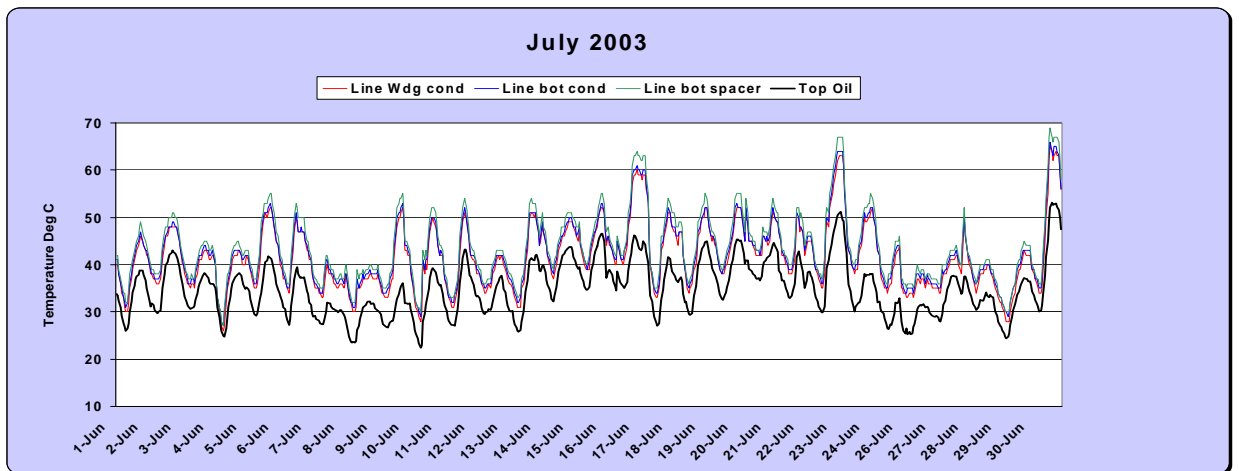


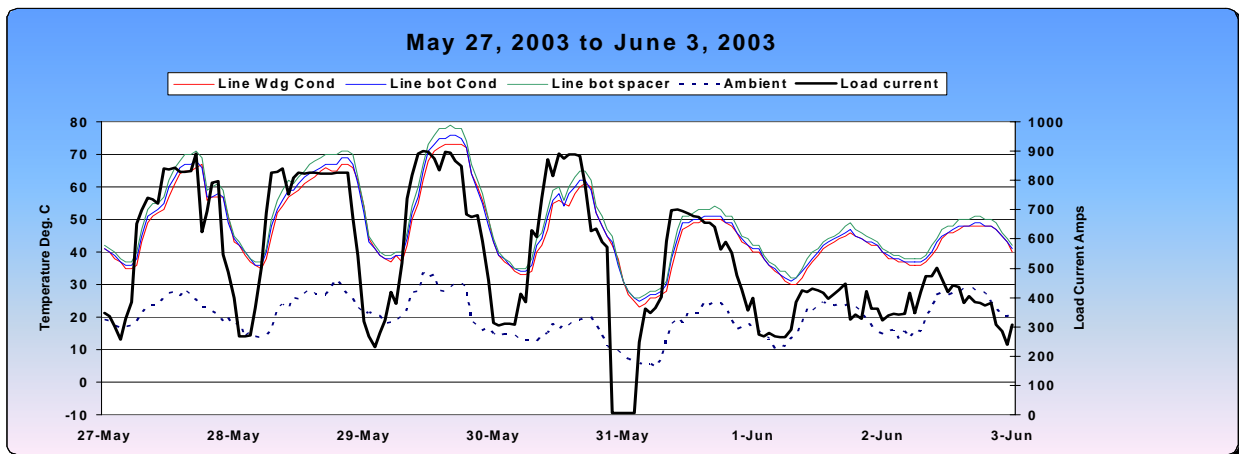
FIGURE 12: Line Winding and Top Oil Temperature Measurements for Month of July 2003

It is observed, (FIGURE 11 and 12) that there is a very significant difference between the winding temperature and the top oil temperature, more so in January than in July. This raises the questions about the accuracy of the IEEE thermal model which is based on a top oil temperature measurement and simple relationship between this and the hottest-spot temperature.

The IEEE model that bases its calculation on the top oil temperature under overloading conditions underestimates the hottest-spot temperature by taking into account the top oil temperature instead the winding cooling duct and/or conductor temperature. The availability of direct measurements by fiber optic sensors may help to improve the hot spot calculations and therefore the thermal model.

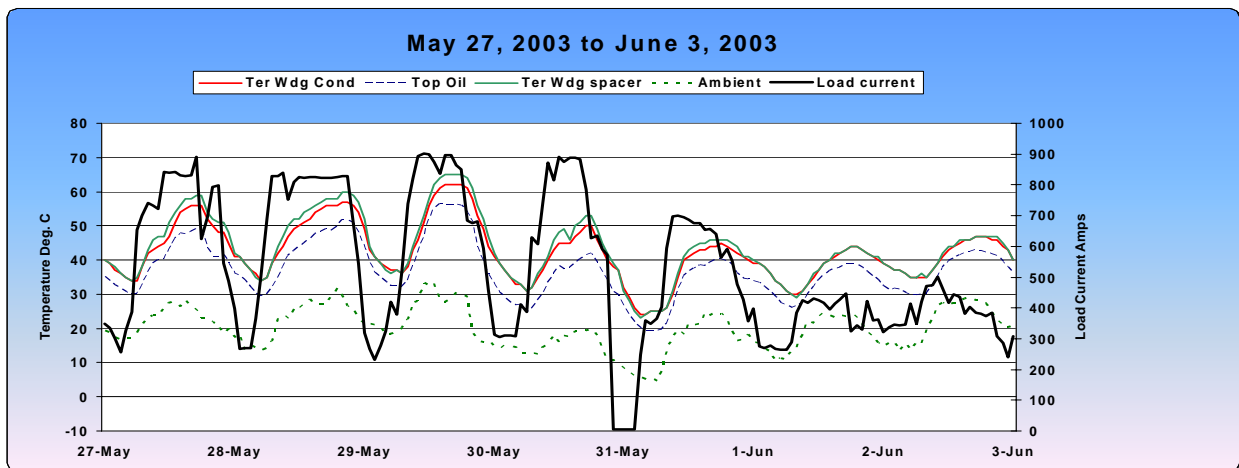
The IEEE model, clause 7 of the loading guide is producing lower hot-spot temperatures than calculated by the direct measurements. The consequence of that is if the unit operates under overloading conditions, the rate of aging will be four times higher than believed and there is a high risk of bubble formation. In addition, the model does not take into account the change of winding resistance with the temperature.

From the operational point of view direct measurements by fiber optic sensors with the data logger provide the opportunity to quickly overview the number of events where the set trigger values were exceeded. These analyses can provide a very reliable estimate how much of the lifetime of the transformer was spent due to say frequent overloading. By having a history of thermal stresses of the transformer we can make a good correlation to the DGA and/or Furan analysis. Our comfort level in decision making about the overloading transformers has increased.



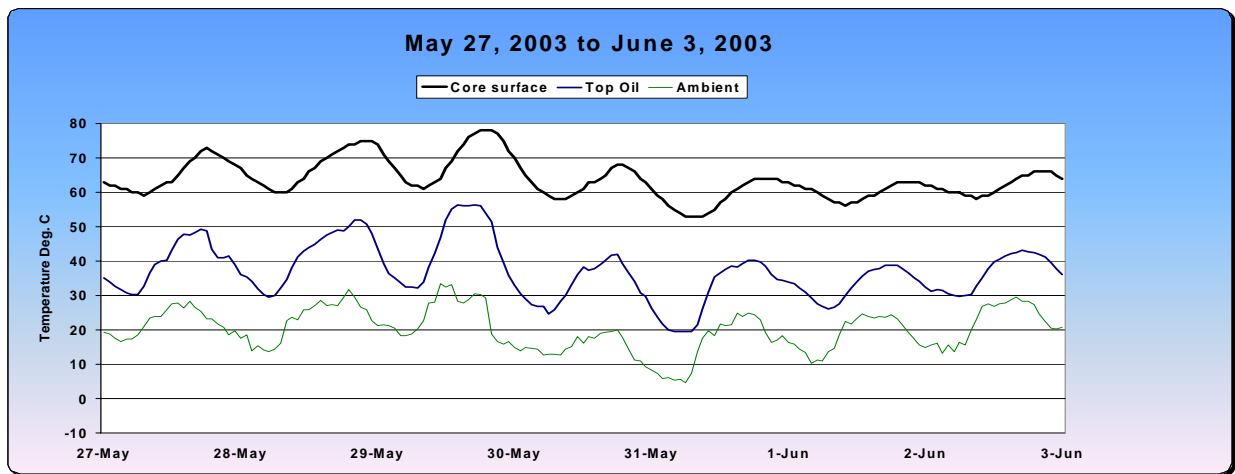
**FIGURE 13: Three Line Winding Temperatures Relationship To Load Current And Ambient Temperature**

The Figure 13 shows dependence of the winding temperatures (light weight top traces) on the load current (heavy trace) and ambient temperature (bottom dotted trace). The transformer was out of service for short time (May 31st) and it was under light load after. There is an obvious dependence on the load current. The contribution of the ambient temperature can be noted on 29<sup>th</sup> of May when for the same load current (approx. 900 Amps) as on 30<sup>th</sup> of May the winding temperature has increased solely due to increase in ambient temperature. The same could be said for the decrease in winding temperature on 30<sup>th</sup> of May following the drop in ambient temperature, while the load current remained at the level of approx. 900 Amps.



**FIGURE 14: Tertiary Winding Temperature Relationship To Load Current And Ambient Temperature**

The tertiary winding (Figure 14) is running about 10°C cooler than line winding for the same period as Figure 13. The dependence on the load and ambient temperature is similar.



**FIGURE 15: The Iron Core Surface Temperature Relationship to Top Oil and Ambient Temperature**

The Figure 15 clearly illustrates that the iron core surface temperature is much higher than the top oil temperature (middle trace) for the same observation period as in Figures 13 and 14.

#### CONCLUSION

Direct measurement of the transformer interior temperatures by fiber optic sensors provide very useful information to those concerned about the level of thermal stresses and the management of life cycle of the transformers. In a period of heavy overloading an on-line temperature monitoring is available. The log of all events during the life time of the transformer is available for analysis. The estimate of the remaining life of the transformer is more accurate.

Immediate knowledge of the winding hot spot temperature provides the comfort zone and the distance to the point of bubble formation. The existing thermal models and loading guides could be improved with respect to accuracy. The DGA and Furan analysis become more meaningful.

With the increased number of applications of fiber optic sensors the manufacturers of the transformers will achieve the levels close to 100% sensors that are working. The manufacturers of the fiber optic sensors will make further improvements with respect to robustness and easy handling of the sensors. With the increased volume it is expected that the price of the conversion of optical to electrical signals will be significantly lower.

*\*Ahmed Glodjo recently retired from Manitoba Hydro. He was authorized to stay as a project leader for “On-line monitoring of transformer temperature” project until its completion.*

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