HOT SPOT STUDIES FOR SHEET WOUND TRANSFORMER WINDINGS

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ABSTRACT

Application of sheet windings is common practice for distribution transformers but is usually only applied to small power transformers. While high eddy losses do occur in some part of the sheet winding a 10 MVA unit has been design and tested to meet IEEE requirements on winding hot spot temperature. Finite element analysis was used to determine the location and magnitude of highest loss density. Thermal modeling was validated with direct measurement of temperature. Fiber optic temperature sensors have been successfully deployed during the temperature rise test to demonstrate accuracy of thermal modeling and loading capability of this prototype transformer.

INTRODUCTION

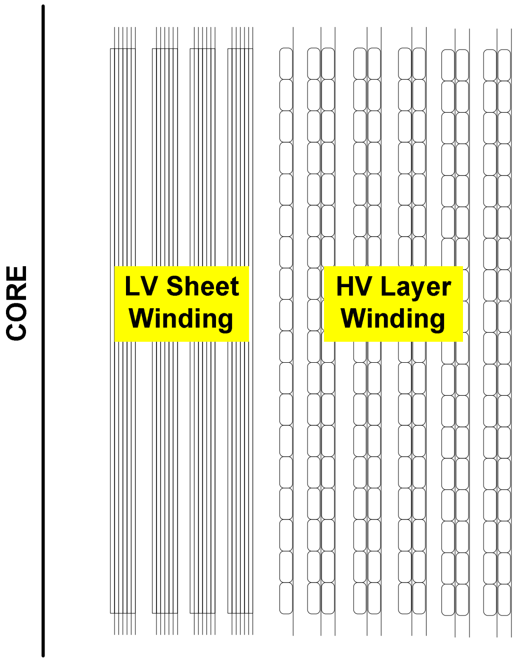
In the distribution transformer industry, sheet windings are very common for low voltage windings. (The term “foil winding” is often heard but is usually refers to thickness lower than 10 mils). Sheet windings often provide significant saving in the manufacturing time and cost. It also provides a unique axial strength against short circuit forces exerted on the windings in case of through fault. However it is recognized that eddy losses near the edge of the sheet can be several times higher than the I^2R losses. This concentration of heat generated at the edge of the sheets is a legitimate concern for the designer of the transformer in terms of insulation life duration and overload capability.

Efficient use of equipment requires that loading capability be well defined. The normal method for hot-spot temperature calculation, based on temperature rise test results is not readily applicable as it is not intended for such high concentration of losses within a small area of the sheet winding. Therefore specific design method and test procedure had to be deployed.

WINDING LAYOUT

A prototype 10 MVA 13.8 kV Delta to 4.160Y / 2.4 kV was designed with copper sheet used for winding conductor on the low-voltage winding. Basic rating is 10 MVA with ONAN cooling mode. It can also be operated at 12.5 MVA with ONAF cooling mode. The winding layout is shown on Figure 1. The low voltage winding is made of a 36 inches wide copper sheet, 60 mils thick. Four packets are separated by cooling ducts with each packet comprising 10 turns of copper sheet.

The HV winding is a layer type winding with flat conductors regrouped in 6 packets. The packet closest to the LV winding has only one layer while the other packets have two layers.



Winding Layout for a 10 MVA Transformer 13.8 / 2.4kV
Figure 1

WINDING HOT-SPOT TEMPERATURE CALCULATION

Calculation of winding temperature involves several critical steps:

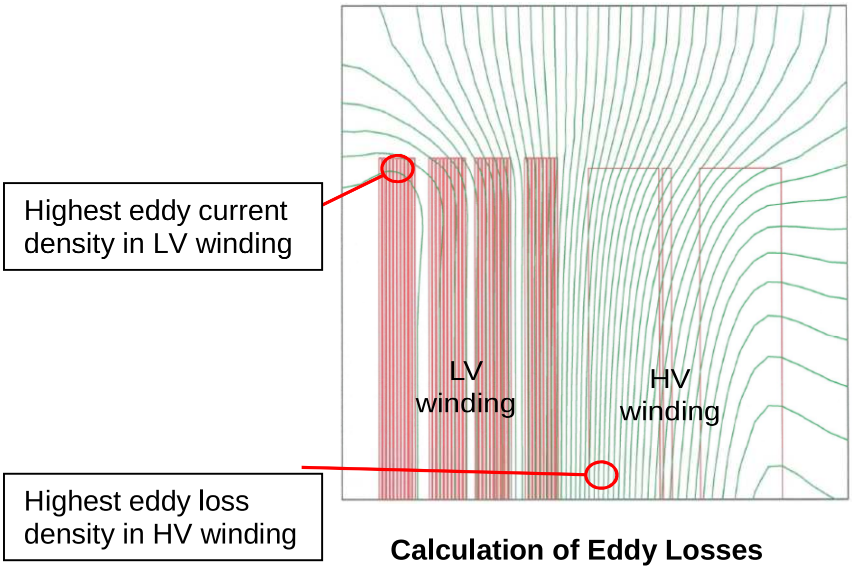
- Accurate modeling of the magnetic field in the winding
- Localization and calculation of the most severe eddy losses
- Calculation of heat conduction along the sheet
- Calculation of heat transfer from conductor to oil
- Calculation of cooling oil flow

Finite Element Analysis

The location and magnitude of most severe density of eddy losses in the winding were determined by application of the Andersen FLD12, Finite Element Analysis program. This program also known as Complex Potential Transformer Leakage Flux is especially convenient for eddy current problems [1]. For the purpose of the analysis, the LV sheet winding was divided into 4 radial segments which correspond to the packets of winding sheets between cooling ducts. The HV winding was divided into 6 radial segments corresponding to the packets of layers between cooling ducts. The FLD program has the ability to discriminate the analyzed winding to very small area of highest per-unit losses.

For analysis, the FEA program divided the sheet into a stack of rings of varying axial width. The top portion of the sheet was modeled with four 2.16 mm rings. The calculated eddy current density in the topmost ring was 4.96 times the nominal current density determined by dividing the rated current by the area of the cross section. The highest loss density was calculated to be in the top ring of the model.

On the HV winding, the location of the highest losses was 12.6 inches from the top on the first layer across the LV to HV cooling duct. In this area the eddy loss density was 0.217 times the I^2R losses of that winding.



Calculation of Eddy Losses
Figure 2

Calculation of Hot-Spot Temperature

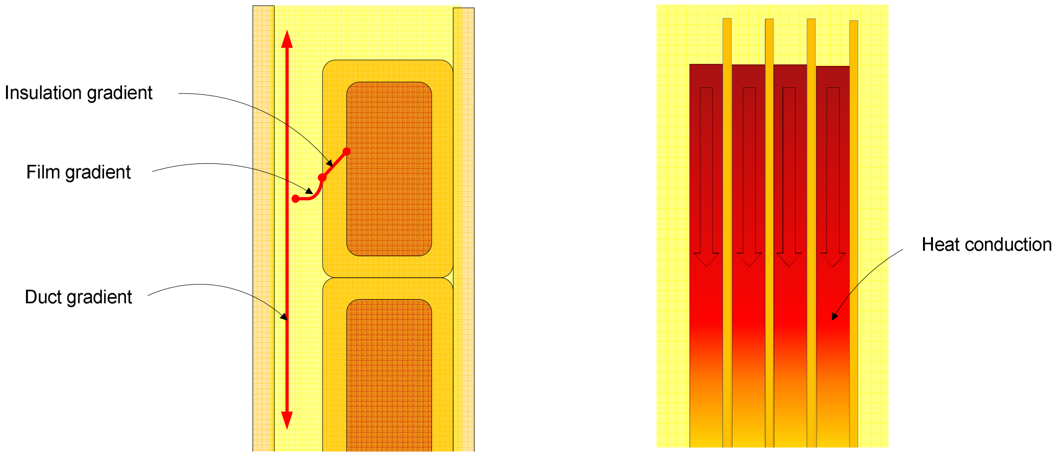
Determination of hot-spot temperatures involve calculation of three separate elements of thermal gradients which are added to the temperature of the oil entering the bottom of the coil. As shown in Figure 3, these three elements are the insulation gradient, the film gradient and the duct gradient. In the case of a sheet winding, the additional factor of conduction of heat within the sheet is to be considered and calculated.

The **insulation gradient** is a function of the total thickness of paper between the conductor and the cooling oil, and the thermal conductivity of oil soaked thermally upgraded Kraft paper. A conservative approach was used for determination of paper thickness. All the paper between the turns or layers at the center of an analyzed segment was included even if the highest loss density was in the turn on the outside of the segment. Highest loss density was still applied to this arrangement.

The **film gradient** is the difference between the temperature of the conductor or paper exposed to the cooling duct and the average temperature of the liquid in the duct. The movement of liquid in the ducts is a laminar flow. The calculation for temperature drop in the film considers the thermal conductivity of the oil and the geometry of the cooling duct.

The **duct gradient** is the difference between the temperature of the cooled oil entering the duct and the heated oil leaving the duct. It is calculated as a function of the specific heat of the liquid and the free convection flow of the liquid based on the geometry of the duct and the buoyancy of the oil given its viscosity and density at various temperatures.

The **heat conduction** within the copper sheet is also an important factor. In sheet windings, near the extreme axial edges of the sheet, the eddy losses can be 4 to 5 time higher than I^2R losses. However, the ability of the copper to conduct the extra heat from this area down through the copper, into area of much lower loss density is quite effective. This conductive cooling of the hot-spot in a copper sheet is much greater than the cooling given by the transfer of heat to the liquid.



Thermal Gradients within Sheet Winding
Figure 3

Winding Hot-Spot Calculation Results

Temperature calculation results can be summarized as follows for operation at 10 MVA:

Table 1
Calculated Hot-spot Temperature for Operation at 10 MVA

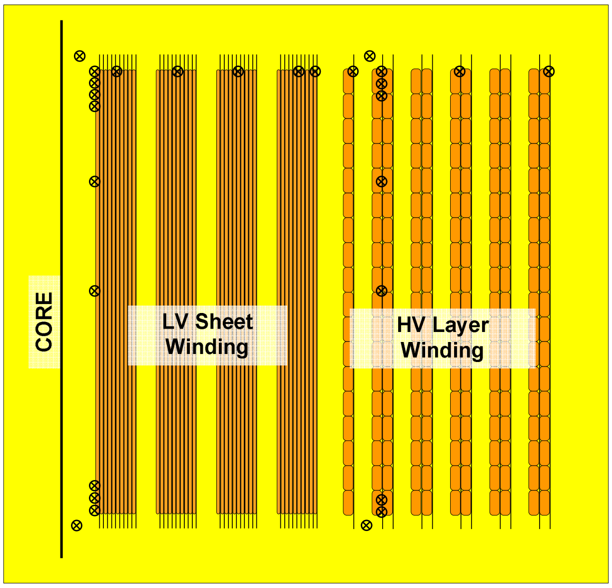
	LV sheet 1-10	HV layer 1 to inner duct	HV Layer 1 to outer duct	HV layer 2 to inner duct	HV layer 2 to outer duct
Average oil rise	56	56	56	56	56
Hot-spot rise over bottom oil	26.1	21.9	18.1	24.6	22.18
Hot-spot rise over ambient	75.3	71.3	67.9	74.4	72.4

FIBER OPTIC TEMPERATURE SENSORS

It was required to use temperature sensors to confirm the values predicted by the thermal model. Measurement of winding hottest spot was performed during the temperature rise test. The temperatures were taken by Fiber Optic temperature sensor (FO).

Location of FO Sensors

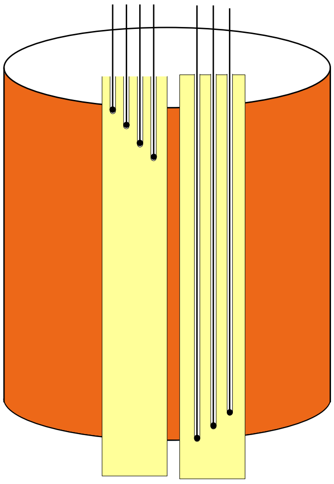
The locations of FO sensors were selected at the point of highest calculated temperatures and also the area of highest eddy loss density identified by the Finite Element Analysis when they were not coincident with the area of highest temperatures. Most FO sensors were located under the top yoke but additional measured points were located around the windings as a control of the uniformity of temperature on the perimeter of the windings, and also to measure the top to bottom oil gradient. Probes were also placed to measure the iron core temperature and the oil just above and below the coils. A total of 44 FO sensors were deployed: 22 in the LV winding and LV oil duct, 17 in the HV winding and HV oil duct and 5 more for core, top oil and bottom oil. Locations of those under the core are shown in Figure 4. External tank temperatures were measured by thermocouples. Ambient temperatures were measured by fiber optics probes and thermocouples.



Location of FO Sensor in LV and HV Windings under the Core
Figure 4

Positioning FO Sensor on a Sheet Winding

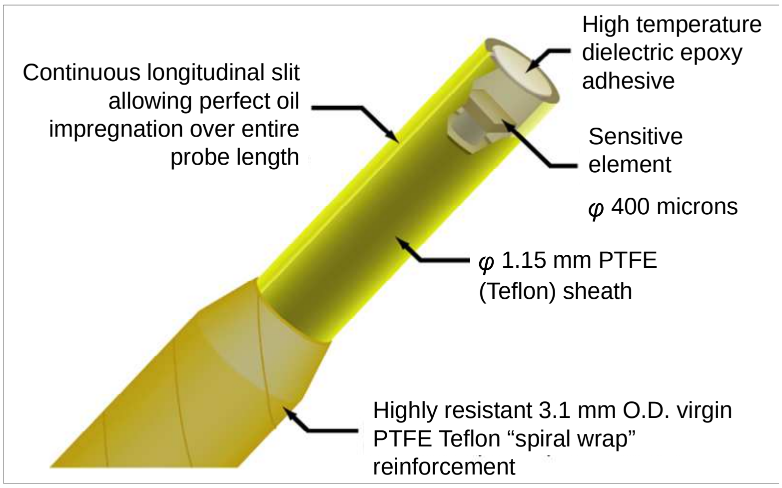
In order to measure accurately the temperature at the edge of the sheet winding a specific method was developed for accurate positioning of the FO sensors. This method is illustrated in Figure 5. On the outside of the first turn, a 1.6 mm (60mils) pressboard is held in place by tapes. Slots were previously cut in this pressboard and the depth of these slots was adjusted to reach the proper position on the sheet winding. The outer jacket of the FO sensor is removed and the sensor is inserted in the slot and glued in place. In order to get the true sheet temperature, the assembly must be such that no oil circulation is allowed on the FO sensor. All leads are coming out at the top of the winding.



Positioning of FO Sensor on the First Turn of the Sheet Winding
Figure 5

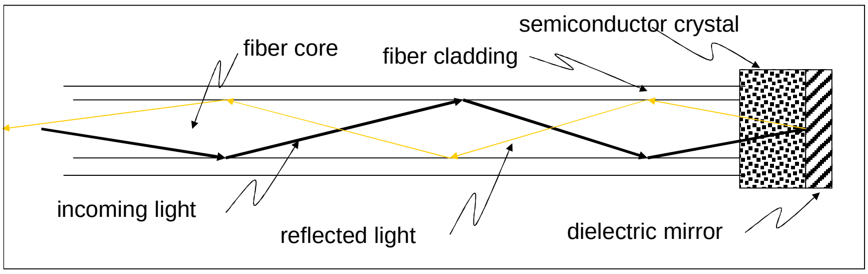
Construction of FO Temperature Sensors

The outer jacket of FO sensor is about 3mm in diameter and is made of Teflon. The inner sheath is also made of Teflon and those protections are designed to allow complete oil penetration, to withstand the drying process of the transformer and to provide high dielectric strength and chemical resistance.



Components of the Fiber Optic Temperature Sensor
Figure 6

FO operating principle is based on the variation in the absorption spectrum of the semiconductor of gallium arsenide (GaAs) with respect to temperature. The fiber core delivers white light to the semiconductor crystal. Depending on temperature, some of the light is more or less absorbed and the rest is reflected back by a dielectric mirror and returns through the same fiber for analysis. This method is depicted in Figure 7. The GaAs 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.



Operating Principle of a FO Temperature Sensor
Figure 7

Routing FO Sensor to Signal Conditioner

For permanent installation and hotspot temperature monitoring the sensor would have to be brought out of the tank through a wall-through fiber optic connector. This method is not practical when 44 sensors have to be brought to the data logger. It was found more convenient to draw the fibers as a bundle, through a manhole on the tank cover as shown on Figure 8. The light signal is then processed, converted to a temperature value and stored in the data acquisition unit. The Neoptix Omniflex system was used for this test program. It provides accuracy of ±1^{o}C and sensitivity of 0.1^{o}C.

Routing the Light Signal to the Signal Conditioner
Figure 8

HEAT-RUN TEST RESULT

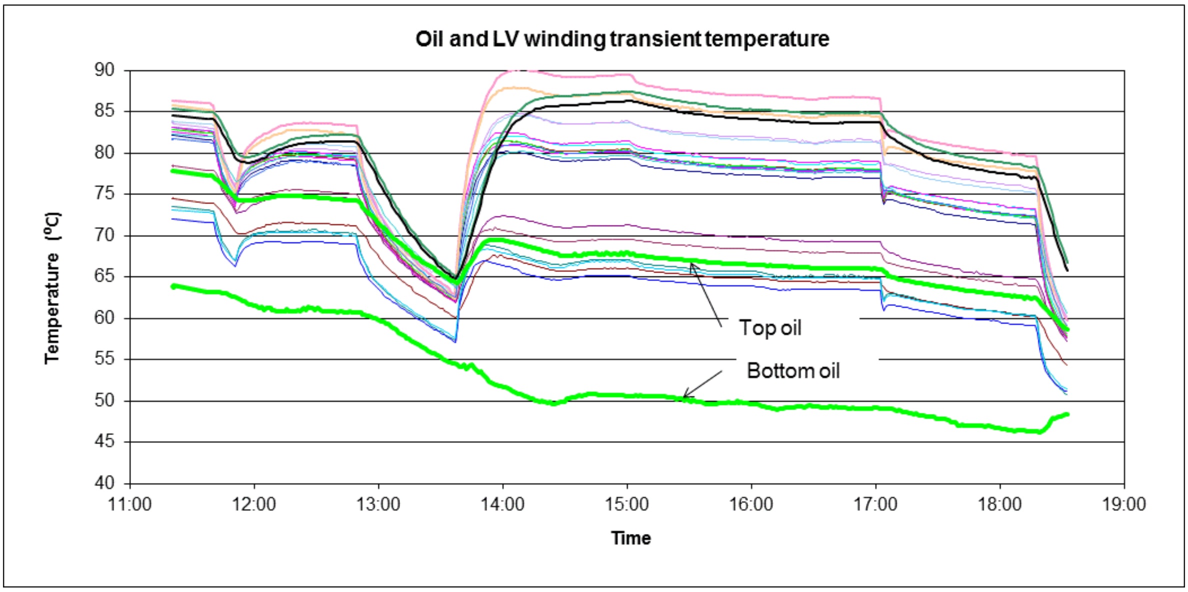
The transformer was submitted to the standard temperature rise test, at 10MVA ONAN and 12MVA ONAF, in accordance with IEEE std. C57.12.90:

- Establish a short circuit condition on one winding
- Applies total losses until top oil stabilizes
- Reduce current to rated value for at least one hour
- Remove AC supply and measure winding resistance.

Beside the fiber optic sensor described above, the transformer was equipped with14 thermocouples placed on the top and bottom of cooling banks, in top-oil and in ambient air.

Dynamic Behavior

Data from fiber optic sensors are recorded every 2 minutes and thus provides a continuous display of temperatures during the heat-run test, as shown on Figure 9. The FO sensors truly in contact with sheet conductor, display a sort time constant upon sudden current change. It can be seen that those FO sensor only in contact with oil will display a much longer time constant. Information extracted from this dataset can also be used for determination of oil and winding time constants.



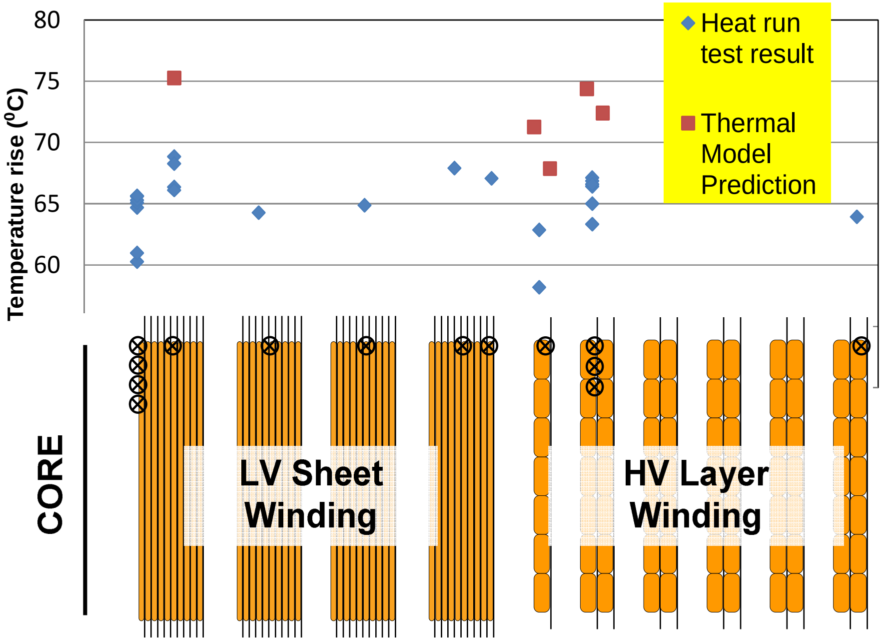
Intimate Contact between FO Sensor and Sheet Conductor is Confirm during Sudden Current Variation
Figure 9

Hot-Spot Rise Validation

FO sensors have allowed measurement of hot-spot temperature at each step of the heat-run test. In the Figure 10 below, the measured values at time of shut down for 10 MVA rating, have been corrected for the oil temperature drop during the one hour at rated current. Therefore, values indicated in Figure 10 are the temperature rise to be expected when the transformer is in operation at rated load of 10 MVA.

The hottest spot in the LV winding is in the middle of the first pack of 10 turns. The measured value, corrected for oil temperature drop during the period at rated current, is 68.9^{0}C. This value is about 6^{0}C lower than predicted by the thermal model based on Finite Element Analysis.

The hottest point on the HV winding is on top of layer #2 as predicted by the thermal model. In this case, the measured value is about 8^{0}C below the predicted value. A summary of predicted and measured values is presented in Table 2.



Predicted and Measured Temperature Rise for Operation at 10 MVA
Figure 10

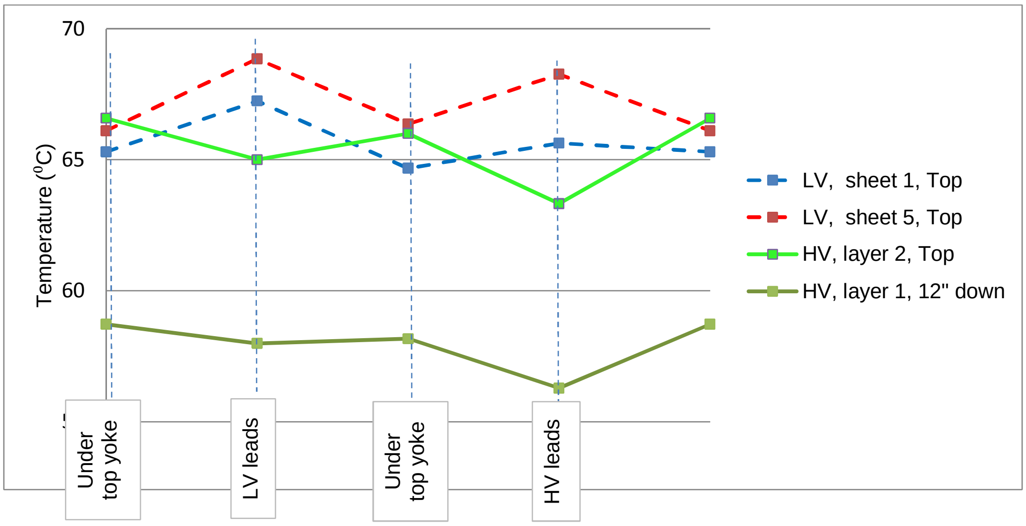
A large part of the difference between predicted and measured values is in the oil temperature. The cooler efficiency is such that the oil temperature is running about 4^{o}C lower than the predicted values.

Table 2
Comparison between Predicted / Measured Temperature Rises

	LV sheet 1-10	HV layer 1 to inner duct	HV Layer 1 to outer duct	HV layer 2 to inner duct	HV layer 2 to outer duct
Average oil rise	**56 / 51.8**	**56 / 51.8**	**56 / 51.8**	**56 / 51.8**	**56 / 51.8**
Hot-spot rise over bottom oil	**26.1 / 23.5**	**21.9 / 17.6**	**18.1 / 17.6**	**24.6 / 21.8**	**22.18 / 21.8**
Hot-spot rise over ambient	**75.3 / 68.9**	**71.3 / 62.9**	**67.9 / 62.9**	**74.4 / 67.1**	**72.4 / 67.1**

Temperature Variation along Perimeter

One factor that is not readily visible from the thermal model is the variation of temperature to be found around the perimeter of the winding. The scattering of the magnetic flux is quite different for the section of winding located outside of the yoke. This difference in the flux pattern leads to some difference in temperature as can be seen in Figure11. The LV sheet winding tends to be about 3 degrees higher outside of the yoke while it is the opposite for the HV conductor winding.



Variation of Temperature along the Winding Perimeter
Figure 11

Fiber optic temperature sensors are increasingly applied in power transformer of special design to confirm winding temperature during temperature rise tests and also in service, to monitor aging of solid insulation. Experience has shown that during manufacturing, the winding hottest spot can always be accessed through the cooling oil channel. However caution must be applied to hold the sensor in a steady position and to prevent oil flow on the sensor itself.

CONCLUSIONS

Low voltage windings made of copper sheet are attractive in regard to ease of manufacturing and high mechanical strength. However these sheet windings do have high eddy losses toward the edge of the sheet. The resulting hot-spot could be a concern for possible accelerated aging especially under overload condition. This problem has been resolved by application of the Andersen FLD12 Finite Element Analysis program that has the ability to analyze every small area of highest per-unit losses. In the LV sheet windings, it is found that a significant part of heat generated by eddy losses at the edge of the sheet is transmitted by conductivity to the bulk of the sheet thus reducing the temperature rise in the hot-spot region.

It was necessary to validate the performance of this design with extensive temperature measurements during the temperature rise test. A method was developed to maintain the fiber optic temperature sensors in close contact and accurate position on the sheet winding. Test result shows that the measured temperatures are 6 to 8 degree lower than expected. This gap is partly caused by a pessimistic estimation of the cooling system. With proper tools for loss calculation and heat transfer modeling, sheet winding designs continue to have a greater application in power transformers in the lower MVA range.

REFERENCES

[1] Andersen, O.W. “Finite Element Solution of Skin Effect and Eddy Current Problems” *IEEE Paper A77 616-6, Mexico City, July 1977*

BIOGRAPHY

Sheldon P. Kennedy, PE is Vice President Engineering with Niagara Transformer Corporation since 1988. He previously was an Engineering Manager with Niagara Transformer Corporation from 1985 to 1988. He had previously been Chief Engineer with R.E. Uptegraff Manufacturing, a Rate Engineer after being a Transmission Substation Engineer with Allegheny Power Service Corporation and worked in Distribution Engineering with the West Penn Power Company. He is a Senior Member of IEEE and a member of the IEEE Transformers Committee where he chairs the Working Groups of IEEE C57.18.10 Semiconductor Rectifier Transformers, IEEE C57.12.52 Sealed Dry Type Power Transformers, and IEEE C57.32 Neutral Grounding Devices. He is past Chair of the NEMA Transformer Section, past Chair of ANSI Accredited Standards Committee C57 – Transformers, Regulators and Reactors, and past Chair of the IEEE Petroleum and Chemical Industry Conference Electrochemical Subcommittee. Mr. Kennedy graduated in 1975 with a BSEE from the Pennsylvania State University.

Thomas Gordner has been a Project Engineer with Niagara Transformer Corporation since 1990. Mr. Gordner had designed transformers with other companies since 1978.

Jean-Noël Bérubé is Global Fiber Optic Product Specialist at Neoptix, a Division of Qualitrol Company LLC. A founding member of Neoptix, he is heavily involved in design and application of fiber optic temperature probes used for hot spot temperature monitoring in power transformers. Bérubé travels worldwide to train transformer manufacturers on how best to install and use fiber optic probes. An electrical engineer and IEEE member with 40 years of experience, his field of expertise has been instrument design and applications where optic, electronics and software are applied together.

Robert Ringlee - Retired; BSEE,MSEE, Phd Mechanics; GE Power Transformer Design Dept. 9 years, GE Electric Utility Systems Engineering 9 years, Principal Engineer and Director Power Technologies Inc. 20 years; Consultant 15 years. Fellow, IEEE, Fellow AAAS.

Jacques Aubin is a transformer consultant especially active in the field of thermal behavior and insulation aging. He was until recently with GE Energy in Montreal where he was mainly involved in development and testing of advance monitoring systems for power transformers. Until1998, Jacques was with Hydro-Quebec in Canada where he directed research activities related to overloading, short circuit strength and acceptance tests on power transformers. Mr. Aubin graduated in 1962 from Ecole Polytechnique de Montreal.