Low-Cost, Reliable Transformer Temperature Sensor

Milestone Report

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ABSTRACT

An accurate, remote monitored, winding temperature device could provide real-time transformer loading information and better decision making under normal and emergency loading conditions. EPRI has initiated a project, "Low Cost, Reliable, Transformer Temperature Sensor," as a feasibility study to review existing methods, investigate new technologies, and make recommendations for the development of prototype instrumentation for determining transformer winding hottest spot temperature reliably, accurately, and economically. The study will focus on indirect methods and simulations using thermal models for retrofit on installed units.

Overheating of transformers is a significant contributor to the accelerated aging of its cellulose insulation structure. Thermal degradation causes mechanical weakening of the insulation and therefore loss of life. For example, a continuous 10ºC temperature increase in hottest spot temperature can cause a 50% loss of insulation life. An accurate temperature sensor will not only help keep a transformer operating at its rated temperature, and therefore maintain its expected life span, but also help diagnose problems such as blocked coolers or cooling fan and pump malfunctions. Additional benefits are the ability to apply thermal modeling to predict future loading capability and the ability to make real-time loading decisions based on actual temperature.

This interim report is a technical summary of existing methods, international standards and third party research into new technologies.

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1 INTRODUCTIO N

An accurate, remote monitored, winding temperature device could provide real-time transformer loading information and better decision making under normal and emergency loading conditions. EPRI has initiated a project, “Low Cost, Reliable, Transformer Temperature Sensor,” as a feasibility study to review existing methods, investigate new technologies, and make recommendations for the development of prototype instrumentation for determining transformer winding hottest spot temperature reliably, accurately, and economically. The study will focus on indirect methods and simulations using thermal models for retrofit on installed units.

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This interim report is a technical summary of existing methods, international standards and third party research into new technologies.

2 CURRENTLY AVAILABLE TRANSFORMER TEMPERATURE INDICATORS

Top oil temperature device

Top oil temperature devices have been in use for many years and are still in common use. These devices utilize thermometers or resistance temperature devices (RTDs) to determine the temperature of the mixed oil near the top of the transformer. The temperature readings obtained from these devices can be used to monitor oil temperature, initiate an alarm or, in some cases, control of cooling equipment.

Winding temperature simulator devices

These devices are commonly applied on all large power transformers. Their purpose is to give better control of cooling equipment than can be obtained with a top oil temperature device. Prior to the development of fiber optic temperature sensors for transformer applications, the winding temperature could not be read directly and had to be simulated. For the most common type of simulators, this is done by adding to the top oil temperature a temperature increment that results from the heat produced by a current proportional to the load current flowing through a heating element. Earlier versions of these devices used a physical resistance to create the additional heat, but this can now be done through calculations performed within the device. Some versions of winding simulators simply add a constant gradient to the top oil temperature.

Although the use of winding temperature simulators is widespread, they have some significant shortcomings. The setting on these devices depends on the hot spot temperature determined by the transformer designer, which may or may not represent the true hot spot. Also, the response of the winding may be different than that of the device. The most serious shortcoming is that the simulated winding rise is added to the top oil temperature. This is another source for error because the oil in a cooling duct adjacent to the hot spot will be higher than the mixed oil temperature at the top of the transformer, thereby, resulting in a winding temperature reading that is too low.

Winding temperature simulators do not have the capability of recognizing a change in the cooling system. If any of the cooling pumps were to become inoperative, the velocity of the oil in the cooling ducts would be reduced and would result in an increase in the winding hot spot rise over which the device was calibrated.

Fiber optic direct measurement

Direct measurement of winding temperature is a relatively new method for determining the temperature of a winding and has been successfully installed in a number of operating transformers. The method supported by EPRI funding uses a phosphor sensor, which is inserted into a winding, and is used to measure its temperature. The sensor is at the end of an optical fiber which is brought outside the tank wall. Both the sensor and the optical fiber are good insulators. The temperature of the sensor is determined by measuring the exponential rate of decay of the fluorescence of the phosphor after a brief pulse of blue-violet light sent down the fiber from a Xenon flash lamp has excited it. Once the rate of decay of the fluorescence as been measured, sensor temperature can be determined by comparison with an empirical calibration curve stored in a digital look-up table.

These fiber optic devices are able to give the most precise measurement of temperature, but in order to utilize them, a sensor must be inserted into a winding where it is wanted to measure the temperature. The sensor is installed in an area that is believed by the designer to be the hottest spot location; however, several sensors are usually installed since the actual hot spot location may not be accurately known. The sensors can also be installed in the winding oil ducts to determine the hottest oil temperature since the winding oil duct temperature may be several degrees hotter than the mixed top oil temperature. The fiber optic cables are taken through pass-through devices to the outside of the tank where they are connected to a read out or to recording equipment. .

Fiber optic devices are able to provide the most accurate measurement of winding temperature; however, recent research[1] has shown that the temperature of the winding conductor will be higher than the temperature of the paper-oil-pressboard interface. For conditions of normal loading, the temperature drop across the paper would not be significant, but it may increase significantly during a short-time overload.

The Need for an Improved Winding Temperature Indicator

Economics is one reason why a more accurate and quicker responding winding temperature indicator is needed. Fiber optic sensors can undoubtedly provide the best indication of winding temperature, but they cannot practically be inserted into the windings of transformers already in service, and their cost for utility application is generally justifiable for new transformers only for the very large sizes and most critical applications.

Utilities need to get all of the capability that their installed equipment is able to provide. In order to dynamically load power transformers and to be able to obtain the benefits from higher loadings requires an economical, but more accurate determination of winding hot spot

[1] Davydov, V., Roizman, O., Bonwick, W., "Transformer Insulation Behaviour During Overload", *EPRI Substation Equipment Diagnostics Conference V*, New Orleans, Louisiana, February 1997

temperatures than the present simulators can provide. More accurate determination of insulation loss of life, which depends on winding hot spot temperature, will also enhance the management of a utility's assets in the long run.

An improved winding temperature indicator is also needed for reliability reasons. It is well known that moisture bubbles can come from a winding when its temperature goes above 140^{o}C. Knowledge about when the conditions are right for this to happen could save a transformer from sudden failure due to a dielectric breakdown. During colder temperature operation, existing winding temperature simulators can cause more cooling system oil pumps to be in operation than are necessary, bringing about the possibility of the static electrification phenomenon and another cause of sudden failure.

More accurate winding temperature measurements are also needed during temperature rise tests made during factory heat run tests. Few transformers are built with direct reading winding temperature sensors and, as a result, there is normally no way of accurately determining if the manufacturer has met the guaranteed winding hot spot temperature rise.

3 IMPROVED WIN DING TEMPERATURE INDICATOR TECHNICAL ISSUES

The currently available winding temperature simulators and direct reading fiber optic sensors have either defiencies or drawbacks. The deficiencies for the simulators are accuracy and time response, while the drawbacks for the fiber optic sensors are their cost and inability to retrofit on existing transformers. If a low cost, reliable transformer temperature indicator is to be developed, a more sophisticated simulation or software solution involving mathematical modelling needs to be considered Such a software-based solution would require addressing and solving three major technical issues.

Adaptability to Changing Conditions

The operating conditions for a transformer do not stay constant, and an improved winding temperature indicator would need to take this into account. If the excitation is constant, oil and winding temperatures for a transformer will depend on the ambient temperature, the current in each winding and the efficiency and/or mode of the cooling system, all of which do not stay constant and can change quickly. Ambient temperature can be easily monitored, but the other two factors involve technical issues that will need to be considered in more detail.

Not only transformers with only two windings, but those with more than two windings will need to be addressed. This would include transformers with two or more secondary windings and transformers with regulating windings. The losses and resulting oil and winding temperatures will depend on the current in each of these windings. For transformers with two secondary windings, the load on each will not necessarily be the same, and the losses in a regulating winding will depend on the setting of the load tap changer. Another technical issue that will need to be addressed is for autotransformers where the current in the common winding is not monitored and the tertiary winding may have load on it.

Besides the ambient temperature and the total losses, the transformer oil and winding temperatures will depend on the efficiency and/or mode of the cooling system. A technical issue that will have to be addressed by any software-based winding temperature indicator is the mode of the cooling system. If the cooling mode changes from self-cooled to forced-cooled, the amount of heat being extracted from the insulating oil changes significantly, and the winding temperature indicator would need to adapt to this change.

Determination of Winding Hot Spot Rise

For new transformers, a good determination can be obtained from the manufacturer of the winding hot spot rise over top oil temperature or over oil temperature at the location of the winding hot spot. These determinations can be made from direct reading fiber optic sensors or by finite element analysis techniques. For older transformers, either of these determinations may not be possible or may be very expensive. An improved winding temperature simulator will need to have available reasonably accurate estimates of winding hot spot rise for different transformer designs.

Determination of a Mathematical Model

A key technical issue is how would a mathematical model for a software-based winding temperature indicator for a specific transformer be determined? Available factory test report data would likely not be sufficient. Special field tests may be required to determine the necessary parameters.

4 INTERNATIONA L STANDARDS AND GUIDES

IEEE

There are several mathematical models in existence that are used to calculate winding hot spot temperature. One of them is contained in the IEEE Guide for Loading Mineral-Oil-Immersed Transformers[2].

The IEEE loading guide equations are based on the premise that the winding hot spot temperature consists of three components. These are:

- The ambient temperature,
- The top oil temperature rise above the ambient temperature and
- The hot spot temperature rise above the top oil temperature.

The last term is commonly called the gradient. The ambient temperature can be either measured or estimated, but the other two terms must be calculated.

The equations for calculating the top oil temperature rise above ambient temperature after a step load change are contained in the IEEE guide. The result of the calculation depends on the following input parameters:

- The load before and after the step change.
- The load loss at rated load and the core loss.
- The top oil temperature rise over ambient temperature at rated load.
- The initial top oil temperature rise over ambient temperature prior to the step load change.
- The ultimate top oil temperature rise over ambient temperature for the load after the step load change.
- An empirically derived number used in an exponential equation to calculate the variation of top oil temperature rise for a change in load.
- The oil time constant

Equations similar in form to the ones used to calculate top oil temperature rise are also contained in the IEEE guide for calculating the winding hot spot temperature rise over top oil temperature. These equations require the following input parameters:

[2]IEEE C57.91-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers

- The load before and after the step change.
- The initial winding hot spot temperature rise over top oil temperature prior to the step load change.
- The ultimate winding hot spot temperature rise over top oil temperature for the load after the step load change.
- The top oil temperature rise over ambient temperature at rated load.
- An empirically derived number used in an exponential equation to calculate the variation of winding hot spot temperature rise for a change in load.
- The winding time constant.
- The winding hot spot temperature rise over top oil temperature at rated load.
- The winding hot spot temperature rise over ambient temperature at rated load.

The data for the last parameter, the winding hot spot temperature rise over ambient temperature at rated load, can be obtained, in order of preference, from direct reading sensors, values calculated by the transformer manufacturer or by assuming a value of 80^{o}C for a transformer rated at 65^{o}C or a value of 65^{o}C for a transformer rated at 55^{o}C.

An alternate set of equations is also included in the IEEE loading guide. They are based on recent investigations that have found that the oil in the winding cooling ducts increases more rapidly than the top oil temperature during a sudden increase in load. This can result in higher than calculated winding hot spot temperatures using the standard IEEE equations, particularly for transformers that are cooled by natural oil flow. To obtain more accurate calculations of winding hot spot temperatures, a revised set of equations have been developed that use the temperature of the oil entering and leaving the winding cooling ducts as parameters instead of top oil temperature. The equations also take into account the type of liquid used for cooling, cooling mode, winding resistance and oil viscosity changes and ambient temperature and load changes during a load cycle. A computer program utilizing the equations and written in Basic for use on a PC is included in the guide.

The revised equations are based on the premise that the winding hot spot temperature consists of four components. These are: (1) The ambient temperature, (2) The bottom oil temperature over the ambient temperature, (3) The oil temperature rise at the hot spot location over the bottom oil temperature, and (4) The winding hot spot temperature rise over the oil temperature rise at the hot spot location.

The input parameters for the computer program are similar to the ones needed for the standard IEEE equations, but with the following among the additional requirements:

- Loss breakdown (I^2R, winding eddy, stray and core losses)
- Tested or rated bottom oil temperature rise over ambient temperature
- Per unit eddy loss at the winding hot spot

Similarly to the standard IEEE loading equations, the revised equations also require as input the winding hot spot temperature over ambient temperature at rated load. The revised equations should result in more accurate temperature predictions, but still require an accurate determination of winding hot spot temperature at rated load as a starting point.

IEC

The equations comprising the mathematical model for the IEC are given in IEC 354, Loading Guide for Oil-immersed Power Transformers[3]. One of the two main differences between the IEC and IEEE methods of calculating winding hot spot temperature is that the IEC equations utilize a hot spot factor (H) to account for the additional heat at the top of a winding caused by increased eddy current losses. This factor varies between 1.1 and 1.5, but is ordinarily assumed to be 1.3 for medium and large power transformers. The hot spot factor is multiplied by the difference between average winding temperature and average oil temperature (g) to obtain Hg, which is the winding hot spot rise over top oil temperature.

The IEC equations for steady state operation make a distinction between natural oil cooling (ON) and forced oil cooling (OF and OD). This is second main difference between the IEC and IEEE calculation methods. For ON cooling, the oil temperatures at the top of the windings are assumed to be equal to the mixed oil temperature at the top of the tank. For OF and OD cooling, the oil temperature at the top of a winding is assumed to be the bottom oil temperature plus twice the difference between the average oil temperature in that winding and the bottom oil temperature.

The steady state winding hot spot temperature is comprised of three components for ON cooling and four components for OF and OD cooling. For ON cooling the three components are: (1) The ambient temperature, (2) The top oil temperature rise over ambient temperature and (3) The winding hot spot rise over top oil temperature. For OF and OD cooling, the four components are: (1) The ambient temperature, (2) The bottom oil temperature rise over ambient temperature, (3) Twice the difference between average oil temperature in that winding and the bottom oil temperature and (4) The winding hot spot rise over top oil in the winding temperature. For OD cooling, an additional correction is made to the winding hot spot temperature to account for the variation in winding resistance with temperature.

As was the case for the IEEE equation for calculating transient transformer temperatures, a change in load is treated by the IEC as a step function. The form of the exponential equation used in the IEC method is the same as the IEEE method.

[3] IEC 354: 1991, Loading Guide for Oil-Immersed Power Transformers

5 CURRENTLY AVAILABLE TECHNOLOGIES

This section identifies the manufacturers of commercially available products that have the capability to simulate or directly measure transformer winding temperature.

Winding temperature simulators

QualiTROL manufactures a wide variety of transformer accessories including both a line of thermometers and electronic temperature monitors for measuring oil and simulated winding temperature.

To simulate winding temperature, the thermometers available from QualiTROL are used in conjunction with additional components consisting of a heater coil which operates from a C.T., an autotransformer which is used to adjust the C.T. output and thermowells which provide an enclosure for the thermometer and heater coil.

The electronic temperature monitors require only the input from a resistance temperature detector for liquid temperature and one or more C.T.s, depending on how many winding temperatures are being simulated. The monitors do not require the heater coils as do the thermometers. Calibration of the winding temperature for the monitors can be done prior to installation on the transformer.

Qualitrol also offers a transformer monitor system that accepts inputs from various sensors, including liquid and simulated winding temperature.

Details concerning their products can be obtained from:

QualiTROL Corporation
1385 Fairport Road
Fairport, New York 14450
(716) 586-1515

Weschler Instruments manufactures a large variety of analog and digital instruments, including oil and winding temperature monitors. Three types of winding temperature monitors are available. The winding temperature is determined as follows for the three types:

- Winding temperature is calculated by adding a simple temperature difference (gradient) to the measured oil temperature. The gradient value is set at the factory and may be re-configured in the field.
- Winding temperature is calculated based on the measured current and oil temperature inputs. Standard IEEE "variables" are used to calculate the winding temperature; however, user-entered variables allow improved accuracy of the calculations.
- Winding temperature is calculated similar to the above, but a third variable, ambient temperature, is used in conjunction with the measured rate of current rise or fall to accurately predict what level of cooling is required.

Details concerning their products can be obtained from:

Weschler Instruments
16900 Foltz Parkway
Cleveland, Ohio 44136
(440) 238-2550

Direct reading sensors

Luxtron is a manufacturer of fiber optic transformer winding temperature monitors that directly measure transformer winding temperatures. The temperature measurement range for their product is from –50^{o}C to 200^{o}C and is accurate to +/- 2^{o}c without calibration.

Details concerning their products can be obtained from:

Luxtron
2775 Northwestern Parkway
Santa Clara, CA 95051
(408) 727-1600

Nortech Fibronic Inc. is a manufacturer of fiber optic transformer winding temperature monitors that directly measure transformer winding temperature. The standard temperature measurement range for their product is from –40^{o}C to 300^{o}C and is accurate to +/- 1^{o}C plus 0.003^{o}C per meter of fiber.

Details concerning their products can be obtained from:

Nortech Fibronic Inc.
500 St-Jean-Baptiste Ave., #240
Québec (Québec), Canada G2E 5R9
(418) 872-4686

Software systems for monitoring transformer winding temperature

EPRI Dynamic Thermal Circuit Rating Program (DTCR2.0) calculates critical temperatures and thermal ratings of power equipment and transmission circuits using real-time measured weather conditions, circuit load, and optional measurements of equipment thermal state. DTCR2.0 calculates a continuous rating, limited-time ratings, and a "time-to-overload" for each piece of equipment and every circuit modeled in the program. Included in these calculations is a determination of transformer winding hot spot temperature. The calculations are the same as those used in PTLOAD V5.0.

The preferred method of determining the initial hot spot temperature rise over top oil at rated load is to obtain it from the manufacturer based on tests documented in the manufacturer's test report. If the measured "hot spot temperature rise over top oil" is not available, it may be possible to obtain an estimated value from the manufacturer based on tests for similar transformer designs. If this parameter cannot be obtained from the manufacturer, PTLOAD V5.0 offers two methods of estimation, designated the "IEEE Standard" method and the "PTLOAD V4.1" method as described below.

"IEEE Standard Method" – (See Section 7.2.6 of IEEE Standard 57.91-1995) If no value is available from the manufacturer, the "hot spot over top oil (HS/TO)" parameter is to be set equal to 15ºC for 65ºC insulation (10ºC for 55ºC insulation) plus the "average winding rise over ambient (AVG CDR/TA)" minus the "top oil rise over ambient (TO/TAMB)".

Example: For a "average winding rise over ambient" of 63ºC (65ºC insulation), with a 50ºC top oil rise over ambient, the "hot spot rise over top oil" is 15ºC + 63ºC - 50ºC = 28ºC.

"PTLOAD V4.1 Method" - In the earlier version of the PTLOAD program, Bill McNutt (the original designer of PTLOAD) suggested the following calculation method based on his experience as a power transformer engineer:

HS/TO = (AVG CDR/AMB - AVG OIL/AMB) * (1.1 + 0.0025 MVArated ^ 0.8) Where MVArated = the rating of the cooling mode

If directed flow FOA or FOW:

AVG OIL/AMB = TO/AMB-2

Otherwise:

AVG OIL/AMB = TO/AMB-(4+0.05*MVArated)

Where:

HS/TO = hot spot temp over top oil (ºC).

AVG CDR/AMB = average winding temp rise over ambient (ºC).

AVG OIL/AMB = average oil rise over ambient (ºC).

The "PTLOAD V4.1" method of calculation typically yields lower defaults for this parameter than the "IEEE Method".

Example: For the DFOA cooling mode of a 60/80/100 MVA, OA/FA/DFOA transformer with an average winding rise of 63ºC, and a top oil rise over ambient of 50ºC, the hot spot rise over top oil is:

HS/TO = (63 - (50-2)) * (1.1 + 0.0025*100^0.8) = 18.4ºC

In certain cases, with OA/FA or OA/FA/FA transformers having ratings in excess of 100 MVA, the "PTLOAD V4.1 Method" may yield unrealistically high values. If the user is in doubt, the IEEE method is preferred and generally conservative. Certified test data from the manufacturer is preferable to either.

Once the starting values of winding hot spot temperature are determined, as described above, the user can choose to use either the "TOP OIL" model as described in IEEE Standard C57.91-1995, section 7-2 or the "BOTTOM OIL" model as described in Annex G of IEEE Standard 57.91-1995. The chosen model is then used as the basis for the dynamic calculations of winding hot spot temperature made by DTCR.

Monitoring systems with diagnostic capability

The following manufacturers are suppliers of monitoring systems with varying degrees of diagnostic capability.

Cannon Technologies Inc. is the developer of the Substation *Advisor*™ system. Included in its diagnostic capabilities is a calculated value of winding hot spot temperature which is determined from monitored oil temperature and load level. The method used for the calculation is not published. Further information can be obtained from:

Cannon Technologies Inc.
1212 E. Wayzata Blvd.
Wayzata, MN 55391
(800) 827-7966

Doble Engineering Company is the developer of the INSITE™ system. Included in its diagnostic capabilities is a calculated winding hot spot temperature which uses a thermal model based on the IEEE loading guide equations. The parameters needed by the thermal model are ambient temperature, high side load current and cooling system status. Additional development of the thermal model is in progress at this time. Further information can be obtained from:

Doble Engineering Company
85 Walnut Street
Watertown, MA 02472
(617) 926-4900

J. W. Harley Co., Inc. is the developer of the SAGE™ system. This monitoring system can accept input from winding temperature simulators or fiber optic sensors, display the readings and give alarms. In addition, diagnostics can be implemented through the use of an equation builder to created user-defined equations for calculating winding temperature based on the monitored parameters. Further information can be obtained from:

J. W. Harley Co., Inc.
9177 Dutton Drive
Twinsburg, OH 44087
(330) 425-1838

6 NEW TECHNOL O GIES—TECHNICAL PAPER SUMMARIES

Numerous technical papers have been written in recent years that address the question of how to more accurately determine winding hot spot temperature. This section contains summaries of some of those papers. The terminology and abbreviations used in the summaries are the same as those used in the original papers even though there may have been subsequent changes.

Determination of Time Constants and Exponents for IEEE Loading Guide Equations by Thermal Testing

A transformer with a hybrid insulation system, consisting of meta-aramid insulation in the hottest parts and cellulose insulation in all other areas, underwent thermal testing utilizing RTDs and fiber optic temperature sensors[4] Temperature measurements were made of top and bottom bulk oil, winding conductor, axial duct oil and radial duct oil for rated as well as above and below nameplate rating. Time constants and exponents that are needed in the IEEE loading equations were determined based on the measurements. When the exponents were used to predict winding and top oil temperatures for loads above nameplate rating, the results were not in good agreement with measured values.

Among the observations from the tests are:

- The oil at the top of the windings is hotter than the top bulk oil.
- The oil temperature rise is not linear as a function of coil height.
- The conductor temperature gradient above axial duct oil is fairly constant for mid-height and top of coil sensor readings, but is only about half of the average winding rise above average oil temperature.
- Analysis of leakage flux distribution showed that the sensors at the top of the coils were not in the area of highest losses.
- Oil duct temperatures rise rapidly following a step load change and has almost the same time constant as the winding.

[4] Zodeh, O. and Whearty, R., "Thermal Characteristics of a Meta-Aramid and Cellulose Insulated Transformer at Loads Beyond Nameplate", *IEEE Transactions on Power Delivery*, Vol. 12, No. 1, pp. 234-248, January 1997

Based on test measurements, calculations were made of winding time constant, winding exponent “m”, oil time constant, and oil exponent “n”.

The calculations for winding time constant were made three different ways using reference temperatures for top bulk oil, axial duct oil and radial duct oil. The top bulk oil temperature changed the least during the test period when the measurements were taken and was, therefore, considered to give the most accurate determination of 5.3 minutes.

The winding exponent “m” was calculated using hot spot temperature over top bulk oil, and two other methods based on average winding temperature over average oil temperature. The values calculated using measured hot spot temperature over top bulk oil (0.930 for ONAN and 0.852 for ONAF) were generally higher than those calculated based on average winding temperature and would result in the most conservative loadings.

The oil time constant was calculated for “heat-up” and “cool-down” conditions. For “heat-up” the time constant was determined to be 3.0 hours. Two values were determined for the “cool-down” condition. When the load was reduced, but not to zero and with losses still being generated, the time constant was determined to be 1.75 hours. When the load was reduced to zero, (power off) the time constant was determined to be 4.35 hours.

The oil exponent “n” was determined to be 0.824 for ONAN cooling and 0.899 for ONAF cooling.

The exponents calculated for “m” and “n” and the IEEE loading guide equations were used to predict top oil and hot spot temperatures for loads above nameplate rating. The results did not agree well with measured values. The exponents were recalculated based on data obtained only at rated and above loads. Calculations based on the revised exponents gave more accurate results.

Improved IEEE Loading Guide Equations that Include Changes in Oil Viscosity and Risistance, Cooling Duct Oil Rise and Hot Spot Location

This research is based on laboratory thermal tests that were conducted on a full-size winding assembly[5]. Steady-state and transient (simulated 150% overload) tests were performed for natural oil flow (OA and FA) and non-directed forced oil flow (FOA) cooling. Thermocouples were used to measure winding and oil temperatures. Measurements taken during the tests were compared with predictions using the IEEE loading guide equations. Because of significant differences, the author proposed modifications to the equations, which take into account changes in oil viscosity and winding resistance with temperature, to give more accurate answers.

During the non-directed cooling flow (FOA) tests, the following was observed:

- The winding hot spot did not occur at the top of the winding during the steady state tests; it occurred at approximately 90% of the winding height
- The hot spot and cooling duct oil temperatures increase significantly during the first ten minutes of the overload test, and then continue to increase at a slower rate as the bottom oil temperature increased.

During the natural oil cooling flow (OA and FA) tests, the following was observed:

- The axial temperature distribution for the steady state test was "less linear" than it was for the FOA cooling test. There were several temperature peaks and valleys along the axial height of the winding.
- The hot spot was in the second turn from the top for the steady state test.
- During the overload test, the hot spot shifted locations.

Winding temperatures during the overload test were compared with values predicted by the equations in the IEEE loading guide. For FOA cooling, the measured hot spot temperature rise averaged about 10^{o}C less than calculated by the IEEE equations. For FA cooling, the measured hot spot temperature rise averaged about 5^{o}C higher than calculated. These facts lead to the conclusion that more accurate equations are needed.

Other researchers have recommended that winding hot spot rise for loading calculations should be based on the temperature rise over the duct oil temperature rather than the top oil temperature. The duct oil temperature rise for FOA cooling at any load can be calculated from:

$$\theta_{do} = \theta_{do,r} [W/W_r]^{.413}$$

[5] Pierce, L. "An Investigation of the Thermal Performance of an Oil Filled Transformer Winding", *IEEE Transactions on Power Delivery*, Vol. 7, No. 3, pp. 1347-1356, July 1992

where:

θ_{do} is the duct oil temperature rise over bottom oil

$\theta_{do,r}$ is the duct oil temperature rise over bottom oil at rated load

W is the watts loss at the specific load

Wr is the watts loss at rated load

The exponent in the equation was determined empirically for FOA cooling. For OA and FA cooling, the exponent can be determined from heat run data at two levels of load. Also, for OA and FA cooling, the duct oil temperature rise is the same as the top oil rise over bottom oil provided all windings in the transformer have similar heat flux. For FOA cooling, a method to determine the duct oil rise at rated load is needed.

A proposed modified equation for determining hot spot temperature at any load is:

$$T_{hs} = T_a + \theta_{bo} + \theta_{wo} + \theta_{hs}$$

where:

T_{hs} is the winding hot spot temperature

T_a is the ambient temperature

θ_{bo} is the bottom oil rise over ambient temperature

θ_{wo} is the duct oil rise over bottom oil at the hot spot elevation

θ_{hs} is the winding hot spot rise over adjacent duct oil temperature

Based on heat transfer correlations, and taking into consideration the change in oil viscosity and change in winding resistance with temperature, the hot spot temperature can be calculated from:

$$\theta_{hs} = \theta_{hs,r} (L^2 K_t)^{.800} (\mu/\mu_r)^{.200}$$

where:

$\theta_{hs,r}$ is winding hot spot rise over adjacent duct oil at rated load

L is per unit load

K_t is the ratio of winding resistance at any temperature to resistance at rated conditions

μ is oil viscosity, centipoise

μ_r is oil film viscosity at rated load, centipoise

Calculations utilizing the proposed equations of hot spot temperature rise over bottom oil temperature that also take into account the changes in resistance and oil viscosity with temperature, compared closely with measured values. For most of the 19 steady state cooling and load current configurations, the difference between calculated and measured values varied between 0^{o}c and 2^{o}C, although there were two with differences of over 4^{o}C. For the overload test, the calculated results compare favorably with the tested values for FOA cooling and for the first 60 minutes for FA cooling.

Based on test measurements, calculations were made of winding time constant, winding exponent “m”, oil time constant, and oil exponent “n”.

The calculations for winding time constant were made three different ways using reference temperatures for top bulk oil, axial duct oil and radial duct oil. The top bulk oil temperature changed the least during the test period when the measurements were taken and was, therefore, considered to give the most accurate determination of 5.3 minutes.

The winding exponent “m” was calculated using hot spot temperature over top bulk oil, and two other methods based on average winding temperature over average oil temperature. The values calculated using measured hot spot temperature over top bulk oil (0.930 for ONAN and 0.852 for ONAF) were generally higher than those calculated based on average winding temperature and would result in the most conservative loadings.

The oil time constant was calculated for “heat-up” and “cool-down” conditions. For “heat-up” the time constant was determined to be 3.0 hours. Two values were determined for the “cool-down” condition. When the load was reduced, but not to zero and with losses still being generated, the time constant was determined to be 1.75 hours. When the load was reduced to zero, (power off) the time constant was determined to be 4.35 hours.

The oil exponent “n” was determined to be 0.824 for ONAN cooling and 0.899 for ONAF cooling.

The exponents calculated for “m” and “n” and the IEEE loading guide equations were used to predict top oil and hot spot temperatures for loads above nameplate rating. The results did not agree well with measured values. The exponents were recalculated based on data obtained only at rated and above loads. Calculations based on the revised exponents gave more accurate results.

Determination of Winding Hot-Spot Temperature from a Conventional Heat Run Test

A method is proposed for determining different values of the K_1 factor used in IEC transformer loading equations based on the rated power, winding arrangement and short circuit impedance of the transformer[6]. At the time this paper was written (1984) direct reading devices for measuring winding hot spot temperature were just beginning to become available. The goal of the paper was to continue efforts to determine the hot spot temperature from the results of a conventional heat run test.

The IEC equation for calculating hot spot temperature is:

$$\theta_h = \theta_w + K_1 (\theta_r - \theta_{mw})$$

where:

θ_h is the winding temperature hot spot rise

θ_w is the top oil temperature rise in the winding

K_1 is a factor, greater than 1.0, which accounts for the unequal temperature distribution at the hot spot location.

θ_r is the average winding temperature rise

θ_{mw} is the average oil temperature in winding

When this paper was published the IEC loading guide recommended a value of 1.1 for the K_1 factor. It was recognized, however, that the factor did not properly account for eddy current losses caused by the radial component of leakage flux. Subsequently, the IEC recommended a K_1 factor of either 1.1 or 1.3, depending on the size of the transformer.

An equation for K_1 that assumes an average value of 10% for the average winding eddy current losses is:

$$K_1 = (s_l^2 + s_{erh}^2)/s_l^2$$

where:

[6] Felber, W., Damm, B., Loderer, K., Preininger, G., "Evaluation of Thermal Conditions of Large Transformers", *CIGRE International Conference on Large High Voltage Electric Systems,* 12-05 pp. 1-8, August 29-September 6, 1984.

s_l is load current density

s_{erh} is eddy current density caused by the radial component of the leakage flux in the hot spot coil

s_{erh} can be determined by:

$S_{erh} = (M)(f)(w)(B_{rm})$

where:

M is a constant

f is the frequency

w is the axial conductor width

B_{rm} is the average weighted radial leakage flux density in the hot spot coil

The above equations show that the value of K_1 is dependent on current density, width of the conductor, flux density and frequency. Other factors also influence the value of K_1, such as, the distance of highly permeable parts from the windings and winding lengths. Taking all of these considerations into account, the authors proposed K_1 factors as shown below for 60hz transformers.

Rated Power (MVA)	**Winding Arrangement**	**K_1 Factor for Short Circuit Impedance of:**		
		<10%	**10-16%**	**>16%**
2.5 to 40	A	1.4	1.5	1.7
	B	1.3	1.4	1.5
40 to 100	A	1.5	1.7	1.8
	B	1.3	1.4	1.5
>100	A	1.7	1.8	1.9
	B	1.4	1.5	1.7

Note: Winding arrangement A is for a winding next to the core, rated less than 30kV, or for windings in double concentric arrangements. Winding arrangement B is for windings located a larger distance from the core than for Winding arrangement A.

A Computer Program that Utilizes Improved Equations for Determining Transformer Hot Spot Temperature

The author proposed an improved set of transformer loading equations[7] than were contained in the IEEE loading guide at that time. Other improvements were also incorporated into the equations and coded into a computer program which is now included in the current version of the IEEE loading guide[8].

The improved set of equations take into account the following:

- The basic equation for calculating winding hot spot temperature is based on bottom oil temperature rise over ambient and the winding hot spot rise over bottom oil temperature.
- Equations, based on fluid flow and heat transfer principles and the conservation of energy, are formulated for average winding temperature, winding duct oil temperature rise, winding hot spot temperature, average oil temperature, top and bottom oil temperature and change of oil viscosity and winding resistance with temperature.

The results of the new computer program were compared with the results of the equations contained in the IEEE loading guide. The comparison was made for a transformer with forced air (FA) cooling and for a transformer with forced non-directed oil flow cooling (FOA). The predictions of hot spot temperature made by the new program were in agreement with test measurements reported in the paper by this author that is titled "An Investigation of the Thermal Performance of an Oil Filled Transformer Winding" and is summarized elsewhere in this report. The IEEE equations for the FA cooling mode resulted in temperatures that were 3.9 to 8.3°C below tested values, while for the non-directed FOA cooling mode, they were 9.1 to 13.5°C too high. The IEEE loading guide in effect at the time this paper was written predicted similar thermal performance for transformers utilizing FA and non-directed FOA cooling. The new equations predict higher winding hot spot temperatures for FA cooling and lower hot spot temperatures for non-directed FOA cooling.

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[7] Pierce, L., **"**Predicting Liquid Filled Transformer Loading Capability**",** *IEEE Transactions on Industry Applications*, Vol. 30, No. 1, pp. 170-176, January/February 1994

[8] IEEE C57.91-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers

Test Methods for Measuring and Factors to be Included in Transformer Thermal Models

The draft of this proposed guide[9] covers test methods for measuring and factors to be included in mathematical models for predicting winding hot spot and average temperature rise over ambient.

The two test methods discussed in the guide are direct measurement by fiber optic sensors and by thermocouples. The guide also covers the factors that should be included in a mathematical model, such as, the flow of insulating fluid within a winding and the distribution of winding losses. The model itself should be based on design data that is known to the transformer manufacturer and supported by tests.

It is also proposed in the guide that winding hot spot rise for a production transformer could be based on a thermal model or direct measurements made on similar units. This would be done by determining a dimensionless "H" factor that would be based on analysis or tests on similar units. The "H" factor would be equal to the difference between winding hot spot rise and top oil rise divided by the difference between average winding rise and average oil rise. The hot spot rise for the unit being tested would then be its top oil rise plus the "H" factor (from the similar unit) times the difference between the average winding rise and the average oil rise.

[9] IEEE P1538/D3.0, Draft Guide for Determination of Maximum Winding Temperature Rise in Liquid Filled Transformers, May 1999

Transformer Network Model Consisting of Thermal Capacitances and Thermal Conductances

A method is proposed[10] for creating a thermal network model of a transformer consisting of thermal capacitances and thermal conductances. Thermal capacitances for each major transformer component can be calculated directly, knowing the mass density, specific heat and volume of each component. Thermal conductances are determined by creating a matrix of driving point and transfer thermal impedances, based on test, and then inverting the matrix.

A distribution transformer was the subject of this study. It was considered to consist of five major components since the temperature of each of them may be different under transient and steady-state conditions. These components are the high voltage winding, low voltage winding, core, oil and tank.

The following equilibrium equation for transient heat transfer is used to calculate the temperature rise for each component:

$$C(dT/dt) + GT = Q$$

where: T is the vector of temperature rise of each component

C is the matrix of thermal capacitances

G is the matrix of thermal conductances

Q is the vector of heat input to each component

For the distribution transformer model, the study considered five thermal capacitances (one for each component) and eight thermal conductances as follows:

G_1 HV winding to LV winding

G_2 LV winding to core

G_3 Core to oil

G_4 HV winding to core

G_5 LV winding to oil

[10] Lindsay, J., "Temperature Rise of an Oil-filled Transformer With Varying Load", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, No. 9, pp. 2530-2536, September 1984

G_6 HV winding to oil

G_7 Oil to tank

G_8 Tank to air

A diagram of the connections of the thermal capacitances and thermal conductances for the thermal network model is shown in the IEEE paper.

The matrix of driving point and transfer thermal impedances can be obtained by injecting a known loss into each part individually and measuring the resulting temperature rise of the other parts. There are two problems with doing this. One is that it is not possible to inject heat in the form of a loss into the oil or the tank. The second problem is that injecting a loss into the core will also produce a significant loss in the winding used for excitation. The author details how these problems are overcome and obtains an accurate matrix of thermal conductances for the distribution transformer under study.

To test the thermal model, predicted and measured responses to a step load increase were compared for the distribution transformer under test. The very rapid temperature rise in both windings was correctly modeled. After eight hours, the temperature for the high voltage winding was computed to be 62.7°C compared to the measured temperature of 62.4°C.

A comparison of predicted and measured temperatures was also made for a typical daily load cycle. Graphs that are included in the IEEE paper show close agreement. The graphs also show that the low voltage winding temperature had the fastest temperature response for a sudden increase in load for this distribution transformer and that the time lag for the core, oil and tank were about the same, but greater than for the windings.

Calculation of Transformer Winding Temperature Using Thermal and Electrical Finite Element Models

A finite element based iterative algorithm is employed to calculate winding temperatures for comparison with actual measurements for a 10kVA test transformer for low-ordered harmonics[11]. The algorithm utilizes both electrical and thermal models. The calculation of harmonic impedances by the finite element method has been described by the author in another paper, therefore, only the thermal analog and finite element models are covered here.

A fifth-order analog circuit is used to thermally model the test transformer. It consists of five nodes which represent the high voltage winding, low voltage winding, core, oil and tank. Eight thermal conductances interconnect the nodes (see the paper for the network diagram). The values of the thermal conductances are determined by tests. This is done by first determining a thermal impedance matrix by injecting D.C. currents separately into the high and low voltage windings and by applying rated voltage to the core to determine resulting temperature rises at the five nodes. The conductance matrix is obtained by inverting the impedance matrix.

Applying the finite element method to a steady state two-dimensional heat conduction equation within the winding cross section results in:

$$\kappa(S)(\theta) = Q$$

where:

κ is the thermal conductivity of the conductors and insulation materials

S is the square matrix with elements defined by the finite element method

θ is the unknown column vector of temperature rises for the winding finite elements

Q is the known column vector of heat loss per unit length in each element.

The steps followed in calculating winding temperature distribution and hot spot temperature are:

1. The electrical finite element method is used to build harmonic winding resistance tables for the high and low voltage windings.

2. A thermal analog model is built in order to determine oil duct temperature.

3. A thermal finite element model is built for the high and low voltage windings in order to compute winding temperature distribution.

[11] Hwang, M., Grady, W., Sanders Jr., H., "Calculation of Winding Temperatures in Distribution Transformers Subjected to Harmonic Currents", *IEEE Transactions on Power Delivery*, Volume 3, No. 3, pp. 1074-1078, July 1988

4. Electrical finite element models are built for the high and low voltage windings in order to compute winding power density distributions.

A comparison of measured and calculated temperature rises for the test transformer showed good results for the five transformer components at five different loss levels. The calculation of the hot spot temperature for the high voltage winding was 4.2^{o}C less than measured. The impact of harmonic currents on the winding temperatures is also covered in the paper.

Calculation of Transformer Winding Temperature Using Coupled Global and Internal Models

A computer model has been developed that predicts winding hot spot temperatures for different types of cooling methods and winding geometries for power transformers[12]. When used as a design tool, it is useful for investigating alternative designs and for obtaining an accurate winding hot spot estimate. The results can be shared with users to aid them in determining transformer loading capability.

The IEC loading guide provides a method for calculating winding hot spot temperature. It starts by determining, by test, the difference between the average winding temperature and the average oil temperature. This difference is defined as the gradient. For power transformers, the gradient is multiplied by a 1.3 hot spot factor. This result is then added to the top oil temperature to determine the hot spot temperature. A CIGRE report in 1995 reported that 60 different load tests on 34 transformers showed that the hot spot factor was distributed almost linearly between 1.0 and 1.5.

An alternative method, which is much more accurate than the IEC calculation method, is to install fiber optic probes in the windings of a transformer. This method provides accurate temperature measurements; however, many probes are needed since the position of the hot spot may not be ~~is~~ not accurately known, and the probes are fairly expensive.

Efforts have been made since 1980 to develop mathematical models that could calculate the hot spot temperature and to determine its location. Hydraulic piping theory was used to determine oil flow velocity. Heat transfer models were then used to compute the local temperature rises. What was not taken into account, however, was the complexity of oil flow within a winding. This has lead to a double coupled model, where one model calculates oil flow velocities and temperatures inside the winding and the other model calculates the oil flow distribution over the windings. The first model is called the Internal Model and the second is called the Global Model.

The Global Model calculates the global oil flow and temperature distribution in a transformer. It is based on hydraulic piping theory and calculates oil flow from pressure differences, whether from oil pumps or natural convection, and an assumed friction coefficient. Every winding is treated as a set of vertical cylinders, and any horizontal oil flow is neglected. The model and its results are explained in a separate paper by the above two authors (and E. Van den Bulck) in a paper titled “Accurate Hot Spot Modeling in a Power Transformer Using a General Network Model”. It was presented at an IEE conference in Cyprus in 1998.

The Internal Model calculates the oil velocity and temperature inside a winding, using the pressure drop over the winding and the inlet oil temperature computed by the Global Model as boundary conditions. The Internal Model also calculates a revised friction coefficient, which it

[12] Declercq, J., Van der Veken, W., “Accurate Hot Spot Modeling in a Power Transformer Leading to Improved Design and Performance”, *IEEE Transmission and Distribution Conference*, New Orleans, LA., pp. 920-924, April 1999.

provides to the Global Model, based on the calculated mass flow through the winding and the pressure boundary conditions.

For calculation purposes, nodes are assigned to various points throughout the windings. Since both hydraulic and thermal equations are solved in the Internal Model, and because the temperatures calculated by the thermal equations have an effect on the hydraulic system, their solution is calculated iteratively. The equations used in the Internal Model are included in the paper. Assumptions made are that the windings are symmetrical about their axes, thereby reducing the problem from three to two dimensions, and that the temperature at each wall side of a disk is uniform.

The results of the model have been compared with tested values. Twelve fiber optic probes were installed in the high and low voltage windings of a 20/40 MVA transformer. A comparison of the measured versus the calculated values is as follows:

	Low Voltage	**High Voltage**
Measured	74.3°C	75.2°C
Calculated	75.5°C	78.5°C

Additional winding hot spot measurements using fiber optic probes are planned.

Comparisons have also been made of measured versus calculated top oil temperature for a larger group of transformers. For ONAN cooling, the accuracy was 2K and for ONAF cooling it was 0.8K. The calculated values were closer to the measured values than those calculated based on earlier empirical methods.

Thermal Model of a Disk Coil With Directed Oil Flow

A thermal model of a disk coil with directed oil flow and a network of oil flow paths guided by washers has been developed[13]. Oil flow through the paths is thermally driven, but pump flow could also be treated with minor modifications. A computer program utilizing the model based on standard thermal and hydraulic principles calculates:

- Oil pressures and velocities
- Oil nodal temperatures and path temperature rises
- Disk temperatures

The model takes into consideration temperature dependent oil viscosity, resistivity, oil density and temperature and velocity dependent heat transfer and friction coefficients. Average winding rise and hot spot temperature can be determined from the output of the program.

A comparison of calculated average winding temperature rise versus measured values during heat run tests is:

	OA		**FA**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**
Average Winding Rise	-0.56	3.19	-0.14	2.38

[13] DelVecchio, R., Feghali, P., "Thermal Model of a Disk Coil With Directed Oil Flow", *IEEE Transmission and Distribution Conference*, New Orleans, LA., pp. 914-919, April 1999.

Dynamic Models for On-Line Calculation of Top Oil Temperature

Dynamic models of transformer top oil temperature are presented in this paper[14] to determine their applicability for use in an on-line monitoring and diagnostic system. As a starting point, the IEEE model of top oil temperature rise over ambient temperature was used, but was found to not accurately match actual top oil temperature measurements. A modification of the IEEE equation was proposed which can more accurately predict top oil temperature.

The IEEE equation for calculating top oil temperature rise is as follows:*

$$\theta_o = (\theta_u - \theta_i)\,(1 - e^{-t/T_o}) + \theta_i$$

where: θ_o is the top oil temperature rise over ambient temperature

θ_u is the ultimate oil temperature rise

θ_i is the initial oil temperature rise

T_o is the thermal time constant

The above equation is the solution of the first-order differential equation:

$$To(d\theta_o/dt) = -\theta_o + \theta_u \qquad \theta_o(0) = \theta_i$$

The IEEE equations for top oil temperature rise over ambient temperature were converted to a discrete-time form for the purposes of prediction and parameter estimation using discrete data points. Two variations of the discrete-time form of the equations were developed. The first, termed Model A, was based on the assumption that the load current is near the rating of the transformer. The equation for

Model A is:

$$\theta_o[k] = K_1\theta_o[k-1] + K_2 I[k]^{2n}$$

where:

I	is the specified load current
K_1 and K_2	are parameters estimated from observed data using linear least squares techniques

[14] Lesieutre, B., Hagman, W., Kirtley Jr., J., "An Improved Transformer Top Oil Temperature Model for Use in an On-Line Monitoring and Diagnostic System", *IEEE Transactions on Power Delivery*, Vol. 12, No. 1, pp. 249-256, January 1997

N is an empirically derived exponent used to calculate the variation of top oil temperature with load.

The second variation, termed Model B, would only be applicable to a transformer that utilizes forced oil cooling (n=1). It was necessary to make this assumption, and the assumption stated above for

Model A, to simplify calculations by using linear least squares techniques to estimate the parameters used in the equations. The equation for Model B is:

$$\theta_o[k] = K_1\theta_o[k-1] + K_2 I[k]^2 + K_3$$

The two variations of the IEEE equations were used to predict top oil temperature for an in-service transformer. For purposes of comparison, readings of top oil temperature were taken at five minute intervals for a one week period. The transformer was rated 336 MVA with FOA cooling. The top oil rise over ambient at full-load and all cooling in operation was 36.2C as reported in the factory heat run test.

The errors between the predicted and measured values of top oil temperature utilizing the two variations of the equations based on the IEEE model were very large. Also, computed physical model parameters were both too high to make physical sense. For example, the top oil rise at full load was calculated to be 268C using Model A of the equations and 59C using the Model B variation. The thermal time constant was calculated to be 1042 minutes for the first variation and 329 minutes for the second. Obviously, the error was very significant, although the results of the second variation were better than the first. It should be noted that the calculated top oil rises cannot be directly compared with the top oil rise reported from the factory heat run test because the data used for the calculations were obtained when only half of the cooling was in operation.

After investigation, it was concluded that the main source of error was that the equations did not properly take changes in ambient temperature into account. A modified version of the second of the two previous equations was developed which did take into account variations in the ambient temperature. Using this equation (Model C), the measured and predicted top oil temperatures were in much better agreement. The authors also suggested the following modification of the above IEEE differential equation to give a better first-order characterization of both loading and ambient temperature variations:

$$T_o(d\theta_{top}/dt) = -\theta_{top} + \theta_{amb} + \theta_u$$

The resulting first-order discrete equation for Model C is:

$$\theta_{top} = K_1\theta_{top}[k-1] + (1-K_1)\theta_{amb}[k] + K_2 I[k]^2 + K_3$$

The mean and the variance of the predicted top oil temperature error using the three equation variations are shown in the table below:

Model	Mean	Variance
A	-1.51	15.0
B	-0.41	8.7
C	-0.00	0.4

Also, the top oil rise over ambient temperature was calculated to be 48C and the thermal time constant was calculated to be 150 minutes.

The authors state in the paper that "large deviations in the difference between measured top-oil temperature and predicted top-oil temperature using the model, we would expect to be able to detect gross cooling system failures, such as failure of one or more pumps, or failure of 20% or more of the fans associated with any pump. Gradual degradation, such as sludge build-up in the radiators would be indicated by an upward trend in the model parameter θ_{fl}. over time."

In discussion following the paper the authors state the monitoring system they have developed includes a model for winding hot-spot temperature prediction, but its accuracy needs to be confirmed with a direct hot-spot temperature measurement.

* Symbols used in the equations have been revised in the latest version of IEEE C57.91.

Calculation of Transformer Temperatures Using an Adaptive, Intelligent Monitoring System

An adaptive, intelligent monitoring system for large power transformers has been developed by the Massachusetts Institute of Technology[15]. At the time the paper was written, the monitoring system consisted of models for temperature and for combustible gas in oil. Other models, such as those for acoustic partial discharge can also be incorporated.

The model based system developed by MIT compares the results of measurements with predictions of a simulation model. The prediction calculated by the gas model, for example, uses stored parameters and oil temperature as inputs. The difference between the measurement and the predicted value results in a residual. A rapid increase of the residual may indicate a quickly evolving fault. A slowly increasing residual may indicate a longer term phenomenon, such as insulation aging or a slowly evolving fault.

The residual is passed to an adaptation mechanism module which tunes the model to each transformer using parameter estimation, thereby, allowing for differences among transformer designs.

The output of the thermal model, utilizing the thermal equations in the IEEE loading guide, were compared with measured top oil temperatures for a power transformer over a period of one week in 1993. The IEEE equations predict a rate of change as follows:

$T_o[(d\theta_o)/(dt)] = -\theta_o + \theta_u$

where:

To is the overall thermal time constant

θ_o is the top oil rise over ambient temperature

θ_u is the ultimate oil temperature rise as defined by:

$\theta_u = \theta_{fl}[(K^2R + 1)/(R + 1)]^n$

where:

θ_{fl} is the top oil temperature at rated load

[15] Kirtley Jr., J. Hagman, W., Lesieutre, B., Boyd, M., Warren, E., Chou, H., Tabors, R., "Monitoring the Health of Power Transformers", *IEEE Computer Applications in Power*, pp. 18-23, January 1996

K is the ratio of actual to rated load current

R is the ratio of load loss at rated load to no-load loss

n is an empirically derived constant

Inaccuracies of both magnitude and phase were encountered which are attributed to the IEEE model not properly accounting for variations in ambient temperature. The thermal time constant is on the order of hours, therefore, the transformer oil temperature will lag behind the daily cycle of ambient temperature changes.

Thermal Modelling for Transformers With Rectangular Layer Windings

Computer subroutines have been developed for use in an overall transformer design program that can optimize thermal performance and predict winding hottest spot temperature for transformers with rectangular layer windings[16]. Use of this detailed design tool can assist the transformer designer to meet IEEE standards and user overload requirements.

IEEE C57.12.00, "IEEE Standard General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers" requires that the winding hottest spot temperature rise not exceed 80ºC when the average winding rise is 65ºC. Common practice for determining the hottest spot temperature rise is to simply add 15ºC to the average winding temperature rise. The next revision of the IEEE standard will require that the winding hottest spot temperature be determined either by direct measurement or by calculation based on fundamental loss and heat transfer principles. If the new IEEE requirement is met by calculation, the results must be substantiated by tests on production or prototype transformers or windings.

The method used by the authors utilizes two dimensional finite difference nodal equations to calculate winding temperature rise over adjacent bulk fluid. The variables in the equations are:

5. Thermal conductance from each node to an adjacent node.
6. Heat generated at each node.
7. Temperature rise over adjacent bulk fluid for an adjacent node.
8. Overall nodal heat transfer coefficient from each node to ducts above or below the node and from the top or bottom of the winding

Input data to the program includes details of the transformer design, such as number, size and location of cooling ducts. Calculations at each node result in a temperature matrix that is a two dimensional representation of the temperature rise over adjacent fluid in the main tank at the same elevation. The temperature rises can be used to determine average winding rise or hottest spot rise. Another program, which uses a finite difference heat balance approach, calculates the insulating fluid rise.

The program was used to calculate winding hottest spot and winding average temperature rise for eleven distribution transformer designs. The number of nodes ranged from 210 to 4050. The sizes ranged from 15kVA, single phase to 2500kVA, three phase. The difference between hottest spot rise and average rise for the small kVA sizes was lower than it was for the larger sizes. The average ratio of hottest spot rise to average rise for the eleven transformers was calculated to be 1.4. The IEC loading guide recommends a ratio of only 1.1.

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[16] Pierce, L., Holifield, T., "A Thermal Model for Optimized Distribution and Small Power Transformer Design", *IEEE Transmission and Distribution Conference,* New Orleans, LA, pp. 925-929, April 1999

Adapting a Transformer Model Based on the State of the System Using a Neural Network

Hopfield neural networks are used to identify variations in the physical parameters of a system in a systematic way, and to adapt a transformer model based on the state of the system. Previous thermal models can make predictions, such as, oil and winding temperatures, but direct fault behavior information (i.e., loss of cooling) is not available. In addition, the Hopfield network is used to design an observer that provides accurate estimates of the internal states of a transformer that can not be accessed or measured during operation[17].

A transformer model is developed which is based on a dynamic third order thermal model and is represented as an electrical circuit comprised of capacitors and resistors. Electrical currents and voltages represent heat flow and temperature, respectively. The core, oil and heat exchanger wall of the transformer are modeled as lumped, isothermal masses. Environmental conditions are modeled as a voltage source. Refer to the paper for a diagram of the circuit based thermal transformer model

To identify system parameters, a realization of the physical based model into an observable canonical form is presented. The state basis is maintained after this realization. The power transformer model is then used to develop an adaptive observer based on Hopfield networks.

To illustrate how the Hopfield based adaptive observer can be used to distinguish between incipient fault conditions and normal operating conditions, a fault was simulated on a 10 KVA transformer. The fault consisted of wrapping the outside of the transformer with insulation. In effect, the insulation changed the system dynamics. Even after the fault was introduced, the Hopfield based adaptive observer was able to predict and track the temperature of the wall, oil and core of the transformer.

[17] Shoureshi, R., Ottele, A., Braun, C., Torgerson, D., Work, J., “Hopfield-based Adaptive Observer Design for Power Transformer Diagnostics”, *EPRI Substation Equipment Diagnostics Conference VII*, New Orleans, LA., pp. II-12-1 to II-12-15, February 1999

7 DISCUSSION OF NEW TECHNOLOGIES

The new technologies that were reviewed in the previous section for obtaining more accurate determination of winding hot spot temperature fall into three main application categories. Their applicability depends on whether the temperature determination is needed for detailed design, planning or operational purposes.

Transformer designers are in need of more accurate tools for determining winding hot spot temperature. IEEE standards will no longer accept the past practice of simply adding 15^{o}C to the average winding temperature rise to determine the hot spot rise. Instead, the winding hot spot temperature will need to be determined by direct measurement or by calculations based on heat transfer principles and substantiated by tests. Calculations will require detailed modeling of transformer windings and finite element analysis to solve the equations. Such detailed calculations, which require detailed knowledge of the transformer winding geometry, would not be practical for an on-line winding temperature indicator, except that the results of such calculations can be used as input for rated conditions.

Utility planners need less detail than do the transformer designers; however, they do need to be able to determine accumulated loss of insulation life and, in order to do this, they need to know transformer insulation temperature as a function of load and ambient temperature. The standard IEEE loading equations as well as the oil and winding time constants and the "m" and "n" exponents have been shown to be in need of improvement. The improved equations developed by Pierce will be of great benefit to the utility planners for the determination of transformer loading policy.

Utility operators need to know winding temperature on a real-time basis in order to properly control cooling equipment and to avoid sudden failures that can result from water vapor or gas bubbles in the oil. The tools that are useful to the transformer designers and the utility planners will not be of much use to the utility operator. Winding temperature simulators and fiber optic sensors can provide real-time information, but the former has known deficiencies relative to accuracy and response time, and the latter is very accurate, but not practical for installation on an in-service transformer and is relatively expensive. Several of the papers were on the subject of thermal network mathematical models. This approach appears to be the most promising one for improving the accuracy of real-time winding temperature indication that could be implemented at low cost.

8 CONCLUSIONS AND RECOMMENDED FURTHER WORK

The two main suppliers of winding temperature simulators for the U.S. domestic market are Qualitrol Corporation and Weschler Intruments. Both of their products are based on measurements of top oil temperature and load current in one or more phases. Weschler now offers an enhancement that calculates the winding temperature based on "Standard IEEE vaiables" which may provide more accuracy than has been obtained from simulators in the past. A quantitative determination of the accuracy and response time for the most technically advanced simulators from Qualitol and Weschler should be determined. This could be accomplished by research that would evaluate the performance of their devices on an operating transformer by comparing the output of each with the other and with the output of a direct reading fiber optic sensor.

The currently available winding temperature simulators can be thought of as crude thermal models; however, more sophisticated thermal models will likely be found to be necessary. The currently available ones were covered in Section 5. These are the two thermal models included in EPRI's Dynamic Thermal Circuit Rating Program and commercial products available from Cannon Technologies, Doble Engineering Company and J. W. Harley Company. National Grid in England and Elin Transformers also have monitoring systems that utilize thermal models and should be further investigated. Similarly to the winding temperature simulators, a quantitative determination of the accuracy of the available thermal models should be determined by evaluating their performance on an operating transformer.

Further development of thermal models and or neural networks would provide the most promise for obtaining the necessary accuracy for winding temperature indicators The proposed thermal network models described on pages 6-10, 6-17, 6-20 and 6-23 are the approaches that should be pursued.

After reliable and accurate thermal models are developed, their cost of implementation would be relatively minor. It is envisioned that such models would require transformer load and ambient conditions as input. The operation of load tap changers and status of the cooling system would also have to be considered, if applicable. Output of the model would be calculated top oil temperature and calculated winding hot spot temperature. Once it is determined that the thermal model is operating properly, a comparison of calculated versus measured top oil temperature could be used to detect deterioration of the cooling system efficiency, e.g., clogged heat exchanger tubes. This kind of diagnostic capablity is unique to thermal models and is a major benefit compared to alternative technologies.

Research is needed to determine the "H" factor as described in the draft of "IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid Filled Transformers". The

"H" factor is equal to the difference between winding hot spot rise and top oil rise divided by the difference between average winding rise and average oil rise. A thermal model can provide an accurate determination of average winding temperature, but the "H" factor would be needed to calculate the hot spot temperature. Use of the IEC value of 1.3 for the "H" factor can no longer be considered as acceptable for all transformer designs.

It would be reasonable to expect that transformer manufacturers could provide values of the "H" factor for transformers recently manufactured. For older transformers, estimated "H" factors need to be established for variations in transformer design, such as, rated kVA, impedance and some details of winding geometry.

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