ADAPTIVE TRANSFORMER THERMAL OVERLOAD PROTECTION

Report by WG K3 - Substation Subcommittee, Power System Relaying Committee

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ABSTRACT

In order to allow power transformers to operate under normal and emergency overload conditions, the present limiting factors to transformer overload capabilities are determined using a conservative interpretation of the heating and cooling equations in IEEE Std C57.91-1995: *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*[1] . Substantial benefits can be obtained by loading power transformers beyond nameplate ratings and thermal algorithms if a reliable adaptive thermal overload protection is implemented. This approach will increase system operation margins by allowing a better use of power transformers during an actual system overload condition.

This paper describes considerations and techniques for the development of adaptive transformer thermal overload protection that is based on the real-time application of the transient heating equations for mineral-oil-immersed transformers as provided in **Guide**[*]. An adaptive overcurrent protection implementation, and the related functional requirements, are discussed in this report.

Comprehensive background information is included.

BACKGROUND

Thermal overload relay settings have in the past typically been calculated from transformer loading capability tables contained in IEEE Stds C57.91-1981[2], C57.92-1981[3], and C57.115-1991[4]. These tables are based on assumed transformer thermal characteristics.

The above documents have since been superseded by the recent issue of the **Guide**. In this revision of the previous documents, loading capability tables are no longer provided. Instead, the user is expected to calculate loadability by applying transient heating equations using the transformer's specific thermal characteristics. In the use of these transient heating equations, the user normally also inputs assumed transformer load curves and ambient operating temperature conditions. These are fixed conservative profiles of loading and ambient temperature.

To optimize the loadability of their transformers (e.g., increased short-time emergency ratings during cooler ambient temperatures), some users have taken advantage of these heating equations to perform real-time transformer loadability ratings calculations. This is done by inputting actual real-time transformer loading and ambient temperatures [5].

With this approach, the loadability rating is no longer a constant value from which thermal relay settings can be simply calculated and applied. Using traditional fixed relay thermal overload settings may unnecessarily limit real-time short-time emergency ratings. Thus, in order to provide adequate thermal protection without limiting loadability, thermal protection will need to be similarly adaptive to the same real-time factors of loading and ambient temperatures that affect the thermal performance of power transformers.

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[*] Throughout this document, "**Guide**" shall refer to the IEEE Std C57.91-1995, IEEE Guide for Loading Mineral-Oil Immersed Transformers [1]

I. Thermal Performance of Mineral-Oil-Immersed Transformers

This section describes basic concepts on thermal performance of mineral-oil-immersed transformers. This is intended to provide the protection engineer a basic understanding of mineral-oil-immersed transformer thermal characteristics and performance in order to help him successfully implement adaptive thermal protection to his power transformers.

A. Thermal limitations

1. Hot-spot Limits [1]

The winding hot spot temperature in the top or in the center of the high or low voltage winding is the most critical parameter in the determination of loadability. It determines the loss of insulation life and indicates the potential risk of releasing gas bubbles on a severe sudden overload condition.

The **Guide** specifies the <u>normal</u> temperature rise of the hottest spot not to exceed 80° C over ambient temperature (ambient of 30° C). This 110° C limit is referred to as normal loading. Furthermore, the **Guide** suggests maximum temperature limits beyond transformer name plate rating. If loss of life (of the solid insulation) is not tracked, then a hot spot winding temperature of 140ºC is an appropriate limiting temperature for long time emergency loading. Hot spot winding temperature of 140° C is considered as a long time emergency loading. During these emergency situations, allowing these hot spot temperature limits may be an acceptable risk but additional calculations are required to determine if the loss of insulation life during these emergency situations is acceptable for a given specific load cycle.

The hot spot temperature is dependent on the ambient temperature, top oil rise over ambient temperature and the winding hottest spot rise over top oil temperature, as defined in section 7.2 of the **Guide**.

The value of the rated winding hot spot rise over top oil ($\Theta_{H,R}$) and the rated top oil rise over ambient ($\Theta_{TO,R}$) are obtained normally by actual tests and the manufacturer's test report.

The hot spot time constant is the time it takes the winding temperature rise over oil temperature rise to reach 63.2% of the difference between final temperature and the initial temperature for a step load change. It may be estimated from the resistance cooling curve during thermal tests or calculated by the manufacturer using the mass of the conductor materials. The hot spot time constant varies with the oil viscosity and the winding-temperature-rise-to-load exponent m. For moderate overloads, it is conservative to neglect the winding time constant and assume the winding hot spot rise over top oil.

2. Top-oil limits [1]

The insulating oil serves as coolant. During overloads, the oil temperature will increase approximately in proportion to the square of the current because the heat generated is predominantly from I^2R losses. Also, due to convection, the highest oil temperature in the transformer tank will be at the top-oil region.

When the top oil exceeds temperature exceeds 105C, it is possible for oil to expand beyond the tank capacity and cause the pressure relief device to operate and discharge oil. Upon cooling, the reduced volume of oil may expose electrical parts, including the bushing connections and the winding, thus, compromising their dielectric strength.

Higher top oil temperatures approaching its 145C flash-point pose a much greater danger of sudden ignition and explosion.

Other components in direct contact with very high temperature oil may suffer permanent deformation, reduction in mechanical strength, and failure during high-level through-faults.

3. Insulation life [1]

Insulation loss-of-life of power transformers is related to a time function of temperature, moisture, and oxygen content. From these parameters, the determining factor to insulation deterioration is the temperature reached by the hottest spot in the winding which usually determines both the thermal aging of the transformer and also, the risk of bubbling when a sudden overload is applied.

The **Guide** recommends that users select their own assumed insulation lifetime estimate. The previous guide used 65,000 hours (7.4 years) as normal life expectancy, based on *50% retained tensile strength of insulation.* In the **Guide**, both Table 3 and section 8.1.2 assume 180,000 hours (20.6 years) as an apparently prudent assumption for normal life expectancy. Further indication of the rationale for this figure is given on page 97 of the **Guide**.

The relationship between **hot spot temperature Θ_H** and **aging acceleration factor F_{AA}** is given by equation (2) of the **Guide**, for 65°C rise transformers:

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\Theta_H + 273}\right]} \quad \text{per unit}$$

where 'per unit' is based on the *normal* aging rate, i.e. the rate that would pertain if Θ_H was the design temperature: 110°C..

For example, if $\Theta_H = 120$°C, then $F_{AA} = 2.71$. This factor is applied to (divided into) the assumed *normal life expectancy* for example 20.6 years, in order to get the actual life expectancy if operated continuously at that temperature: resulting in 7.6 years for this example.

Another way of writing this is in terms of **rate of loss of life ROLOL**:

$$ROLOL = \frac{2400}{180{,}000A} e^{\left[-\frac{15000}{\Theta_H + 273}\right]} \quad \text{per cent per day}$$

where A = 9.80×10^{-18} and the assumed *normal life expectancy* is 20.6 years or 180,000 hours.

So, for the same example (Θ_H = 120°C) we get ROLOL = 0.0361 per cent per day. At this rate, 100% loss of life will occur in 100/0.0361%/day = 2770 days, which is 7.6 years.

4. Ancillary equipment (bushings, leads, current transformers, tap-changers) [1]

Overloading the transformer can have detrimental effects on associated equipment. The bushings, tap-changers, bushing-type current transformers and leads may also be affected by the increased temperature caused by transformer overloading.

Bushings are designed with a hot spot temperature of 105°C for a transformer top oil temperature of 95°C. Operating the bushing above these limits can have damaging affects such as internal pressure buildup, aging of gasket material, increased power factor, bubble formation when the hot spot temperature exceeds 140°C, thermal runaway from increased dielectric loses at high temperatures, and heating in metallic flanges due to stray magnetic flux. For bushings, the following guideline maximum values should not be exceeded:

Ambient air	40°C maximum
Transformer top-oil temp	110°C maximum
Maximum current	2x rated bushing current
Bushing insulation hot spot temp	150°C maximum

Tap changers, whether designed to change taps under load or de-energized conditions, are subject to carbon build-up at elevated temperatures. Overloading and the resulting heat build-up can lead to gas generation. The build-up tends to be wiped away by operation of load tap changers (LTC's) and can be effectively controlled on tap changers designed for de-energized operation by approximately ten operations over the full range of the tap changer at least once a year. Transformers are normally designed so that the LTC rating is greater than the transformer rating. More frequent maintenance is required on LTC's which are subject to operation at elevated temperatures.

Bushing-type ct's have the transformer top oil as their ambient temperature. Overloading the transformer will result not only in higher top oil temperature, but higher ct secondary current as well. The manufacturer should be consulted regarding the capability of the ct if the transformer is loaded beyond its rating.

The insulated lead conductors which provide connections within the transformer to the tap-changers, terminals, etc. are also subject to overheating. However, the loading of the transformer is normally not limited by the rating of the leads.

5. Stray flux heating [6]

The term "stray flux" refers to the magnetic flux external to the transformer core. It consists primarily of the winding leakage flux and the flux produced around the low voltage, high current leads. Winding leakage flux is magnetic flux external to the transformer core. It is significant wherever the flux path enters the tank wall, inducing eddy currents at that point. High currents in the low voltage leads that connect the windings to each other or to the bushings can cause high eddy currents in the structural members supporting the bushings and in core clamps.

Stray flux produces localized heating in any metallic part that is in its field. This heating results from induced eddy current losses, harmonics due to nonlinear loads, and to a lesser degree, hysteresis losses. Under extreme conditions of transformer overvoltage, stray flux increases disproportionately due to core saturation. For either of these conditions, the resulting stray-loss heating will deteriorate liquid and solid insulation.

Modern methods utilize finite-element analysis to predict and control magnetic field distribution during the transformer design process. Older transformers, i.e. prior to the '70's, having been designed with methods less able to predict stray flux paths, may be more prone to stray loss problems during overloads.

Various methods for stray flux control include the use of insulated (non-metallic) supports at the top and bottom of the coil windings, vertical core-clamp configurations, special non-magnetic supports for LV bushings and ct's associated with high-current leads, and tank wall shields (see I.B.5).

6. Bubble generation [7]

Gas bubbles within a transformer are of concern since the dielectric strength of the gases is significantly lower than the dielectric strength of the oil or the cellulose insulation.

Bubbles can form in the transformer from gas generated during faults, nitrogen supersaturation (in nitrogen blanketed transformers) or from overload conditions.

When heat is generated during an overload condition, the dissolved water vapor in the cellulose insulation expands, causing bubble formation. The most important factor in bubble formation is the water vapor content of the transformer.

The temperature at which bubbles begin to form on the hot spot varies considerably based on the moisture content. For transformers which have moisture of about 2% of insulating paper weight, bubbles have been observed to start to form at about 140°C. For transformers with moisture levels of 0.5% or less, bubbles may not form until the temperature is above 200°C.

Note that generated gas tends to re-dissolve, so the effect of operation above 140ºC is reversible; however, loss of life has occurred.

B. Transformer Construction as it Affects Thermal Performance

1. Thermal capacity (core & coil, tanks & fittings, oil)

Heat can flow directly from the core to the oil. However from the coil, heat must go through insulation to the oil. Most large transformers are designed so that at least one side of each insulated conductor can transfer heat directly to the oil. The heat transfer rate is proportional to the insulation thermal conductivity and surface area and inversely proportional to the insulation thickness [8]. Due to the use of spacer blocks and barriers in the construction, heat transfer characteristics are difficult to model.

Even though oil viscosity will decrease as the oil temperature increases, the impact on overall cooling of the transformer due to the natural convection movement of the oil will not be significant [8]. It is important to remember that where the oil flows is just as important as how much oil flows. At some points, the oil may be hotter than at the top of the tank, because at the top of the tank oil from many flow paths are mixed together, yielding an average temperature rise.

The core and windings define the basic dimensions of the transformer tank's length and width, with the tank height determined by the level of oil necessary to cover the core (including tap changer). Additional space for oil circulation is added on to the basic dimensions, providing more significant requirements than the electrical clearances for the tank. Tank design affects the ability of the transformer to dissipate heat to the surroundings. Vertical location of the core and winding within the tank also will influence the rate of heat transfer to the oil; the lower the heat source, the better.

The transformer oil is oxidized and discolored as it is exposed to air at elevated temperatures. The discoloring is due to sludge formation. The deposit of the sludge on the surfaces of the winding insulation will reduce the heat flow from the winding, elevating its temperature. The use of inert gas to minimize sludge formation, combined with oil filtration, control the effects of oil oxidation [9].

2. Cooling equipment (pumps, radiators, coolers)

Corrugating the tank was an early means of increasing the surface area of the tank without increasing tank volume. The radiator cooling tubes now used have a fairly constant heat dissipation rate per unit length [8]. Cooling tubes that are farther spaced will have better heat transfer capability due to the greater possible air flow. The larger the tube surface area, the greater the cooling capability. Some manufacturers use a flat plate design for cooling tubes, allowing more surface area per tube and reducing manufacturing costs. The capability of the cooling tubes are affected by their cleanliness.

Pumps are used to increase the flow of oil, thereby increasing the efficiency of the external radiators and minimizing the temperature difference between the oil at the top and bottom of the transformer tank. The oil path must be designed to flow equally over the surfaces of the coils to obtain maximum cooling efficiency. Any area where the oil remains still will suffer elevated temperatures.

3. Cooling modes [20]

Natural draft (air) cooling is utilized for small transformers. Improving the winding design to allow better ventilation has permitted larger kVA transformer construction; however as the transformer size increases, the cooling surface area is insufficient to dissipate the heat generated by the transformer losses. Additional cooling must then be provided [9].

Oil immersion increases the heat transfer rate of the transformer and the addition of external radiators attached to the tank increases the cooling surface area [9].

Forcing air over the surface of the radiators can substantially increase the rate of cooling above the self-cooled rating. Larger MVA transformers may be designed for either one or two stages of forced air cooling. In general, when two stages of forced cooling are used: 133% of the self-cooled rating for stage one and 167% of the self-cooled rating when stage two comes on. Forcing the air can double the convection cooling, resulting in an increase of the total cooling (convection and radiation) of 2/3 over the self cooled rating [8].

Forced-Oil-Air cooling employs pumps to draw the oil out of the transformer tank to the external radiators. The oil is then redirected over all of the winding surfaces [9]. The overall winding cooling is improved further due to the oil turbulent flow, compared to designs without pumps.

Water-cooling can be used for large transformers when economically justified as opposed to large radiators.

Under emergency conditions, spraying with a hose is sometimes used. It is not a recommended practice since there is failure risk if water is sprayed on the bushings. Also, the water may deteriorate the cooling radiators / heat exchangers over time.

The abbreviations used for the various cooling modes are as follows:

IEEE Std. C57.12.00-1993 Cooling Designations		IEC Equivalent
Self-cooled	OA	ONAN
Forced air cooled	FA	ONAF
Forced liquid cooled	FOA	OFAF
Water cooled	OW	ONWF
Forced liquid and water cooled	FOW	OFWF

IEC (International Electrotechnical Commission) Standard Cooling Designations:
(now the designations for IEEE as well)

O Mineral oil or equivalent flammable synthetic insulating liquid
L Non-flammable synthetic insulating liquid
G Gas
W Water
A Air
N Natural
F Forced (oil not directed) (See the next section)

D Forced - directed oil (See the next section)

1st letter	2nd letter	3rd letter	4th letter
Indicating the cooling medium that is in contact with the windings.		Indicating the cooling medium that is in contact with the external cooling system	
Kind of cooling medium	Kind of circulation	Kind of cooling medium	Kind of circulation

For example: ONAF indicates "Oil with natural circulation, and Air with Forced circulation (fans).

4. Oil Circulation

Heated oil will naturally rise vertically. An inherent path for oil circulation is provided by vertical ducts. Many winding designs rely on horizontal ducts for cooling, employing some means such as baffles to force the oil in a zig-zag path through the windings [10]. In this way the oil effectively cools all of the exposed winding surface. The maximum natural oil cooling occurs if the area heating the oil is located at the bottom of the tank and the cooling area is located at the top. A relationship between transformer tank vertical dimensions and the natural cooling efficiency has been demonstrated [8].

Transformers may be classified as **non-directed flow** or **directed flow**. As defined in the C57.12.00 and in the **Guide,** in non-directed flow transformers the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced through the windings. Directed flow transformers are designed so that the principal part of the pumped oil from the heat exchangers or radiators is forced to flow through the windings.

5. Stray flux shields

The effects of stray flux can be reduced by designing the transformer to minimize the flux in metallic components, utilizing non-metallic materials, minimizing the perpendicular dimension of metallic materials to the flux path, and use of internal tank wall shielding. Stray flux shields are used where the flux path would enter the tank wall [11]. Strips of aluminum or steel are commonly used for this purpose. Sometimes stainless steel strips are used for breaking flux paths and patterns. Aluminum or laminated steel strips are used to change flux patterns and paths on the main tank wall. This feature will reduce the losses and heating by eddy currents, which were developed by the flux paths on the main tank. It should be recognized that residual current flux due to unbalanced transformer currents can flow through the flux shield, causing it to overheat.

6. Oil Preservation Systems

During operation under heavy load the transformer oil level will rise above the initial fill level due to the operational temperature increase. All oil-filled power transformer designs have some means of providing space for oil expansion. The most common ones are the conservator tank or a gas space in the main transformer tank above the oil. If the transformer is overfilled, under moderate to heavy loading conditions, oil may be released from the pressure relief device if there is insufficient space to contain the expanded hot oil.

7. Auxiliary Cooling Equipment

A thermally operated control device or a manually operable switch can be used for control of auxiliary cooling equipment. The thermally operated control device, measuring the top-liquid temperature, is used in an automatic control system. The auxiliary system will provide for the appropriate initiation of the cooling equipment, and is a major part of transformer construction.

C. Sources and sinks of transformer heating

1. No-load losses (hysteresis, eddy current)

No-load loss is a source of transformer heating. It is present whenever the transformer is energized. This loss is made up of hysteresis and eddy current losses in the transformer core. Hysteresis loss results as the elementary magnets within the material seek to align themselves in the presence of alternating magnetic field. Eddy current loss is I^2R loss in the core material and is due to eddy currents induced by alternating magnetic field in the core magnetic material. [12]

Eddy current loss is proportional to the square of the thickness of the core lamination. Core material of good permeability and low conductivity reduces eddy current loss. For cold rolled grain oriented silicon steel used in modern large power transformers, the hysteresis loss and eddy current loss are approximately equal.

Hysteresis loss varies as the average value of the exciting voltage while eddy current loss varies as the rms of the exciting voltage. No-load loss increases rapidly at excitation voltages above 110%. At elevated voltages, overexcitation occurs for which a separate protection scheme is used. [13]

The foregoing discussions of no-load losses assume that the power system that the transformer is connected to has purely symmetrical AC currents and voltages. The presence of largely DC GIC (Geomagnetically Induced Currents) flowing in the power system through the grounded neutral connection of a transformer can cause the magnetic flux in the core to be biased such that the transformer experiences severe saturation on each half cycle of the AC voltage. The result will be large no-load losses that are not predicted by the normal models. In GIC prone areas, when applying adaptive loading algorithms, it may be desirable to sense the presence of GIC and include a factor for this additional heating in the transient heating equations to de-rate the transformer during a GIC event. [23]

No-load loss is typically small compared to load losses. Nevertheless, it is taken into account in the equations for ‘top oil temperature rise,’ using the factor ‘R.’ See section B.3 in part II of this document.

2. Load losses (copper, stray)

Load losses in transformers consist of two primary components: (1) *copper loss*, due to the winding resistance, and (2) *stray load loss* due to the eddy currents induced in other structural parts of the transformer. The *copper loss* has two components: *dc resistance loss*, and *winding eddy-current loss*. In all cases the predominant component of the losses is proportional to the current squared.

The effect of the changing temperature on the losses is more complex. The load loss associated with the dc resistance of the windings is proportional to the temperature change of the windings since the dc resistance is also proportional to temperature. The load loss associated with the eddy current component of the resistance is inversely proportional to the temperature change since the eddy current magnitudes will decrease when the resistance of the eddy current paths increases.

The *stray load loss* associated with eddy currents induced in other structural parts of the transformer (steel tank, clamps, etc.) is also inversely proportional to temperature for the same reason that eddy currents winding resistance losses are lower. For the calculations of losses the only difference is the thermal coefficient of resistivity alpha which is different for steel than for copper. *Winding eddy current loss* and *stray load loss* in modern transformers are small but should not be ignored in thermal calculations.

3. External (sun loading)

A number of factors affect solar heating: Solar Beam Angle, Solar Azimuth, Solar Altitude, Standard Direct Beam Intensity, Diffuse Sky Radiation, and Thermal Radiation. [5] However, the total effect on transformer heating is not significant and is normally neglected in protection calculations. In July/August, 1991, laboratory tests were conducted on three 16.8/22.4/28 MVA transformers at LILCO and the test data were presented at the 1992 PES summer meetings. This report documents a peak Solar Heat Flux of 750 Watts/sq. meter on manual OA cooling of the second transformer at Plainview Substation, and 1000 Watts/sq. meter on FOA cooling of the third transformer at Plainview Substation, and 1000 Watts/sq. meter on FOA cooling of the third transformer at Plainview Substation. Because of limited effect of solar heating the ANSI/IEEE standards do not account for solar heating on transformers.

4. Wind, water-spray

Compared to forced-cooling, wind has negligible cooling effect. Since forced-cooling will be in operation during overloads, wind effects need not be included in the adaptive protection model. Water-spray, on the other hand, can provide significant heat-dissipation and temperature reduction. However water-spraying is an abnormal cooling method, applied only as a last resort by some utilities, to control excessive operating temperatures during severe overloads. The cooling effect of water-spraying is not included in the transient heating equations.

D. Transformer Performance Characteristics

The **Guide** provides guidelines to determine top-oil and winding hottest spot temperature rises of transformers at loads other than nameplate rating. Loading guidelines are based on loading equations combined with empirical data accumulated during years of experience of loading transformers.

Certain investigations carried out by transformer users have raised concerns about the accuracy of the equations and the empirical constants used in the equations of the loading **Guide**. Whether these investigations will eventually change the **Guide** or the way it is used, remains to be seen.

The need to accurately predict ultimate temperatures attained by the oil and the winding during overloads led to the formation of an IEEE Transformer Committee working group. The goal of the working group is to publish a standardized test procedure for performing temperature rise tests on transformers at loads beyond the nameplate rating, PC57.119[14]. The intent of these tests is:

- to obtain data on thermal characteristics to determine empirical constants used in the loading guide equations,
- to demonstrate that the transformer meets loading capabilities without exceeding temperature limits as agreed upon by the manufacturer and the user,
- to verify that the ancillary equipment would not impose limitations on loading as recommended in loading guides.

1. Heat-Run Tests

All parameters required are specified in C57.12.90[17][α] . Three additional optional tests are described in PC57.119[14]:

- The first one, Clause 9 of the draft, covers a test procedure for performing a series of temperature rise tests to determine parameters required to calculate the thermal performance of the transformer using the equations from the loading guide.
- The second test, Clause 10 of the draft, describes procedures for tests which demonstrate a transformer's capability to be loaded with a specific sequence of loads.
- The third procedure, Clause 11 of the draft, is an integrated procedure to determine thermal characteristics parameters as well as to verify the loadability of the transformer at specified loads.

Temperature rise tests are performed either at 70%, 100%, and 125% of the maximum nameplate rating or at specified loads depending on the test procedure followed. During the test, current is held constant to simulate losses at these loads and various parameters such as ambient, top-oil and winding temperature, input currents and losses at different loading levels are monitored or recorded. This data is used to verify the thermal characteristics of the transformer.

The procedure also specifies the order in which these tests are to be performed. Temperature rise tests are started with rated load test followed by the 70% load.

[α] IEEE C57.12.90-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers, and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers

Before starting the 125% load test, preliminary exponents “m” and “n” (see section B.3 in part II of this report) are calculated and used to evaluate top-oil temperature or winding hottest spot temperatures at 125% load. If these values are in excess of the values agreed upon by the manufacture and the user, the load may be reduced from 125% such that top oil temperature and the winding hottest spot temperature and oil levels are limited to acceptable levels.

A recently published paper [15], points out certain disagreements with the loading guide assumptions. The thermal testing was conducted, in accordance with PC57.119, to determine the oil- and winding-to-load exponents “n”, “m” and the oil and winding time constants for use in the loading equations. The transformer was tested at loads approximately equal to 70%, 100%, and 125% of the maximum rating using the constant current method. In addition to traditional instrumentation for measurements, the transformer was equipped with an array of fiber optic temperature sensors for direct measurement of duct oil, bulk oil and conductor temperatures. Also, at the completion of the testing, oil from the transformer was analyzed for the presence of combustible gases.

The following observations were made:

- The top tank oil was cooler than the oil at the top of the coil.
- Oil temperature gradient is not a linear function along the coil.
- The temperature gradient of the winding above local oil was constant , but was only half of the average winding rise above average oil.
- The thermal characteristics of the transformer under test, for loads above the nameplate rating appear to differ from those for loads below the nameplate rating. The values of exponents “m” and “n” calculated from data obtained at and above rated values result in more accurate temperature rise calculations for loads above nameplate rating.
- Oil time constant was shorter during heat up conditions than that during final cool-down.
- Winding time constant was dependent on the oil temperature at the start of the cool down period.
- Transformer has inherently higher capacity than indicated nameplate rating.

2. Temperature rise parameters

Temperature rise tests done in accordance with PC57.119 provide data to determine the following thermal characteristics of the transformer.

a. Top oil temperature rise over ambient: $\Delta\Theta_{TO}$
b. Average winding temperature rise over average oil temperature: $\Delta\Theta_{W}$
c. Winding hot spot temperature rise over top oil temperature: $\Delta\Theta_{H}$
d. Oil exponent: n
e. Winding exponent: m
f. Thermal time constant of transformer oil temperature rise: τ_{TO}
g. Thermal time constant of winding temperature rise: τ_{W}
h. Oil level change with respect to top oil temperature change.

The use of these parameters in the equations of the **Guide** is presented in a later section.

II. Real-time (adaptive) thermal protection

This section describes real-time application of the transient heating equations defined in the **Guide** for adaptive transformer thermal overload protection.

A. Present thermal overload protection practices including available commercial product

Overheating may be caused by high ambient temperatures, failure of the cooling system, delayed clearing of an external fault, overload, or severe abnormal system conditions (for example low frequency or overvoltage). Slight overheating will result in accelerated loss-of-life of insulation, and severe overheating may result in immediate insulation failure or may initiate gassing and ignition of gases and cooling oil.

Presently, there are several methods for monitoring transformers to help protect a transformer against thermal overload and failure[18]. The most commonly used devices are:

Oil and embedded temperature sensors
Thermal and replica relays
Sudden oil/gas pressure relays
Gas detection relays
Oil level detectors
Fuse/Overcurrent relays
Condition monitoring equipment

Some of these devices have limited ability to detect and/or limit transformer overheating.

1. Direct Temperature Sensors

In existing transformers, resistance temperature detectors (RTDs) or thermocouples (TCs) cannot be used to measure hot spot temperature directly because they are essentially at ground potential. Fiber optic sensors are the only practical means.

A non-electrical thermometer element immersed in the top oil of the transformer is the most commonly used sensor for thermal overload protection. This element is equipped with contacts which can be used to start cooling fans or pumps or sound an alarm. It does provide a good indication of "steady-state" or slowly-changing temperature change, but not "transient" or fast-changing temperature rise. In other words, since this temperature measurement represents bulk oil temperature, it suffers from the inability to quickly detect sudden transformer overloads or sense localized hot spots.

2. Thermal and Replica Relays

These relays are used to simulate transformer hot spot temperature. Two forms of relay are used: an oil-immersed thermal relay and a replica relay. These relays can also be set to start additional fans/pumps, alarm, or trip the transformer depending upon the simulated temperature.

The thermal relay is immersed in the top oil of the transformer. It contains a heating element, which is supplied with a current proportional to the winding currents. Generally the relay is designed with a time constant longer than that of the winding. Since insulation deterioration only occurs over time at elevated winding temperatures, this time constant permits short-time overloads until winding temperature limits are reached.

The replica relay is another means of simulating transformer winding temperature. This relay also uses a current proportional to the winding current, which is passed through heater units inside the relay. The design "replicates" the time constants of the oil coolant, iron core, and windings, and the relay can be installed outside of the transformer tank in the ambient air around the transformer.

3. Sudden Oil/Gas Pressure Relays

The sudden gas pressure relay is mounted in the gas space above the oil and consists of a pressure-actuated switch. It operates on the difference between the pressure in the gas space and the pressure inside the relay. An equalizing orifice permits equalization of these two pressures for slow changes in gas pressure. The oil-pressure relay is mounted in the oil below the minimum oil level in the tank.

For internal transformer faults, the sudden pressure difference will activate the switch. These switches are sometimes set to trip breakers to de-energize the transformer.

4. Gas Detection Relays

These mechanical devices can only be used on transformers equipped with conservator tanks. It detects the evolution of small quantities of gas inside the transformer. Given its ability to detect small quantities of gas being formed inside the transformer, the relay can detect accelerated insulation aging due to overloading, high-resistance electrical joints, high eddy currents between core laminations and low- and high-energy arcing within the transformer.

5. Fuses / Overcurrent Relays

These devices are applied to protect the transformer from severe damage due to electrical faults. Both types of devices utilize or "monitor" main transformer winding current to operate. Given that high electrical currents can result in high transient heating of the transformer windings, these devices do provide some limited thermal protection of the transformer.

6. Adaptive Overcurrent Relays[19]

This idea is based on a simple premise: a transformer can be loaded more in cold weather than it can in hot weather. The user logic is this:

(1) Decide on a criterion for permissible continuous loading. For example: Normal rate of loss of life over a day. If constant loading is assumed, this corresponds to a specific hot spot temperature, as determined from the equations in the **Guide**.

(2) From this temperature, use equations (2), (4), (5) and (6) of Section **II B 3** ***Equations for the Clause 7 Approach*** to find the allowable steady-state load, **K** , for various values of steady-state ambient temperature

[Note that in the steady-state, equation (2) becomes $0 = \left[\Delta\Theta_{TO,U} + \Theta_A\right] - \Theta_{TO}$.]

A sample result, for self-cooling is shown in Fig. 1. [hot spot rise = 25ºC, top oil rise = 55ºC, m = 0.8, n = 0.8, R = 3.2 . These parameters are explained in section B.3 of this report.]

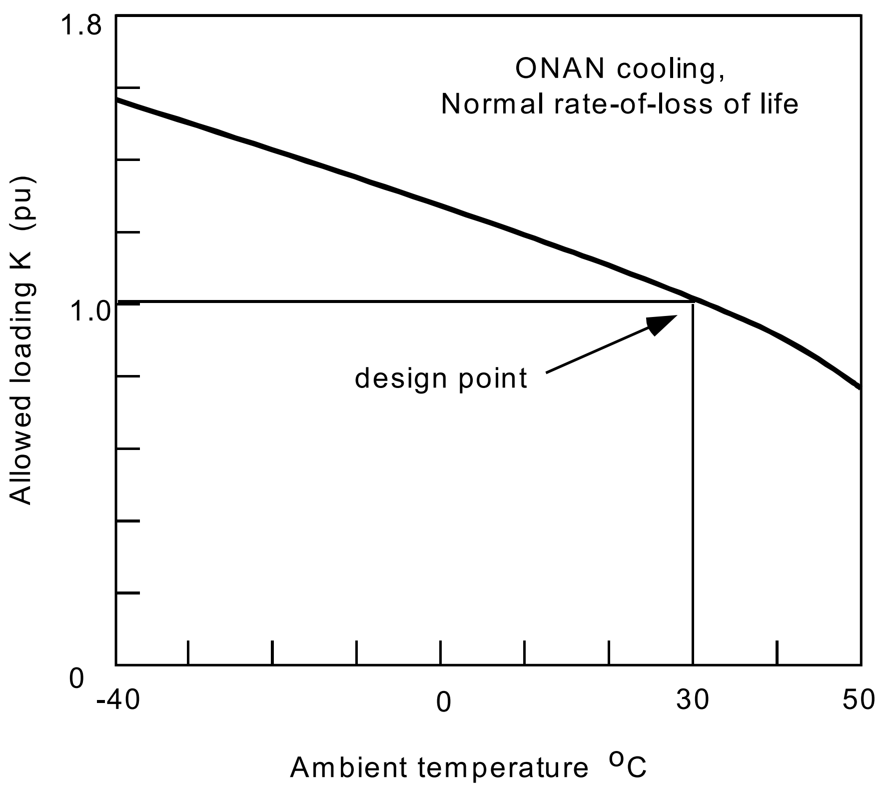

Fig. 1. Above-rating/de-rating curve

Thus the 'adaptation' of the overcurrent relay pickup setting would be (for example) about 1.55 per unit (instead of 1.0 per unit) at -40° C.

The adaptation takes the form of movement of the overcurrent relay function pickup level, as shown in Fig. 2. There is a manufactured product that incorporates this feature.

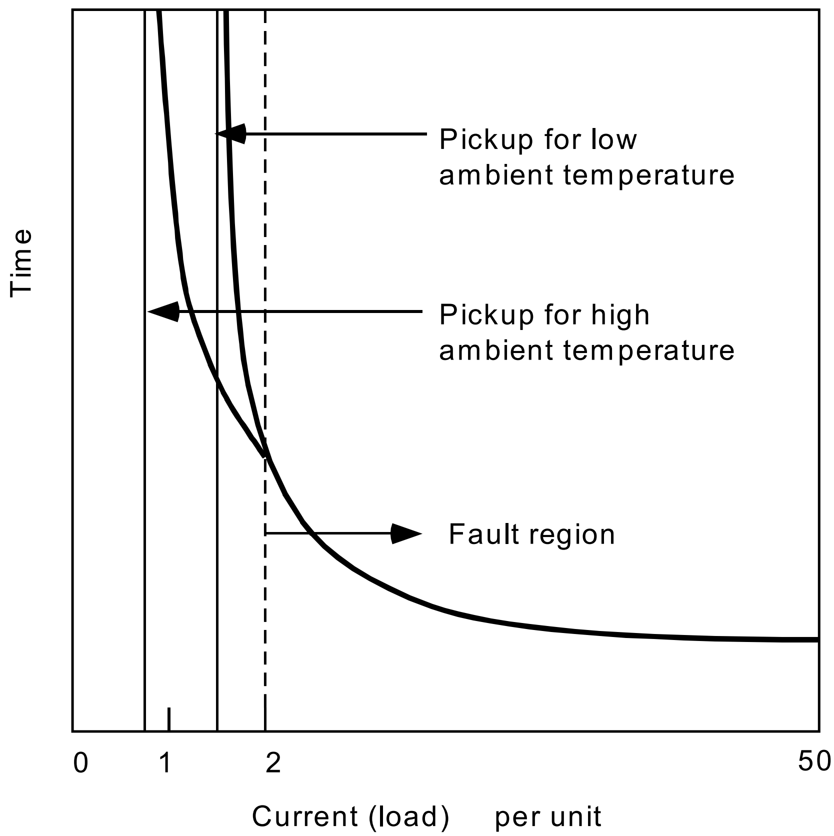

Fig. 2. Inverse time overcurrent relay with adaptive pick-up

7. Condition Monitoring Equipment

This equipment is used for diagnosis of internal transformer conditions. Unlike thermal or replica relays, this equipment does not attempt to mimic transformer heating. It uses software to calculate expected hot spot temperatures from actual operating conditions, such as transformer loading, ambient temperature, and top oil temperature. This equipment is used for monitoring steady-state operating conditions which are detrimental to the transformer and will alarm if a detrimental condition is detected.

B. Transient heating equations

1. General Principles

Let us limit the initial discussion to *oil temperature rise*. *Winding temperature rise* will be discussed later.

For electrical engineers, an electric circuit analogy is instructive. Consider the drawings in Fig. 3.

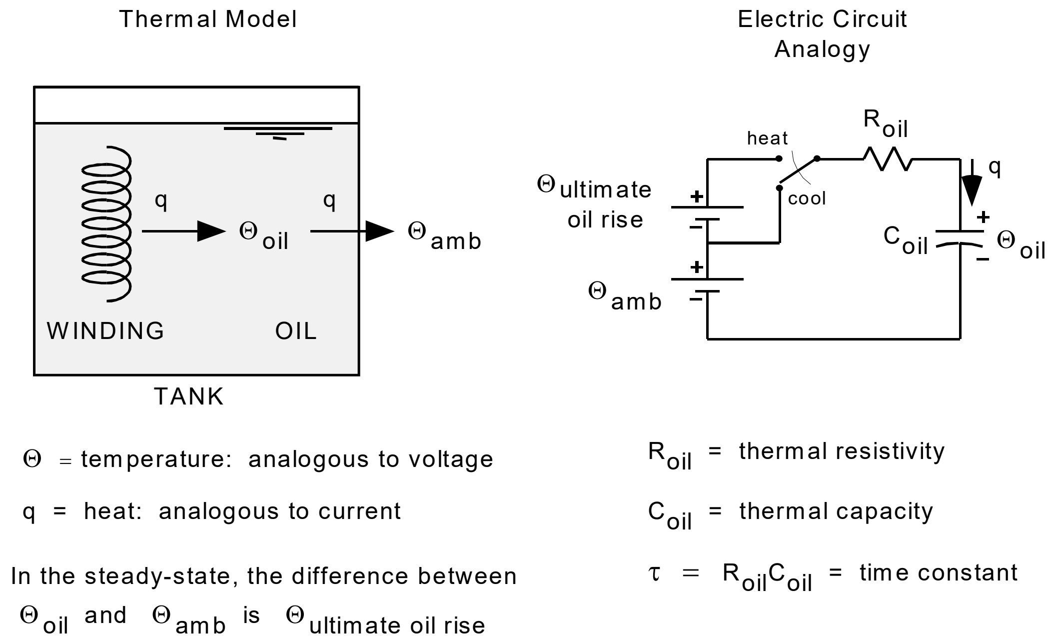

Fig. 3 The thermal model and its electric circuit analogy.

Figure 3 gives an intuitive grasp of the heating and cooling processes, and the implied exponential rise and fall of voltage (temperature) that would occur when the switch is moved from "cool" to "heat" or vice versa, as shown in Fig. 3. The responses are shown in Fig. 4.

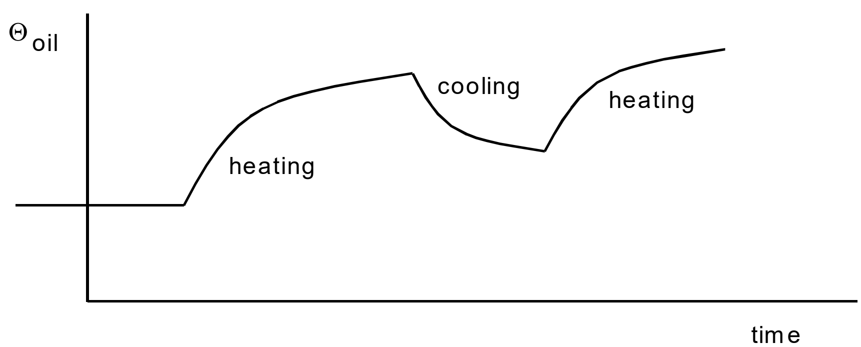

Fig. 4 Heating and cooling responses.
(switch position movements in the circuit analogy)

However, this particular circuit analogy is unduly restrictive. The input need not be "switched dc." The differential equations are equally valid for completely general internal heating and ambient temperature fluctuations. See Fig. 5.

In this representation, for any *ultimate oil rise temperature* or *ambient temperature* the *oil temperature* may be calculated by a numerical solution of the implied differential equation:

$$R_{oil}C_{oil}\frac{d\Theta_{oil}}{dt}=\left[\Theta_{ultimate-oil-rise}+\Theta_{amb}\right]-\Theta_{oil} \qquad (1)$$

The next step is to add the *hot spot temperature rise* phenomenon to the above equation.

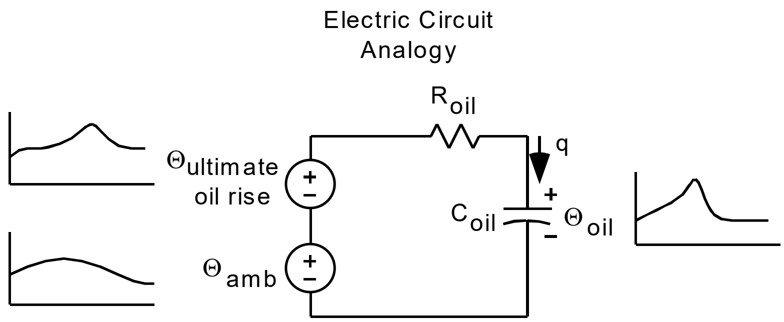

Fig. 5 Generalized electric circuit analogy

2. An Expanded Model

The thermal model of Fig. 3 can now be expanded to include the effect of high temperatures close to the winding(s) of the transformer, the highest value of these being the "hot spot temperature." There is more than one way to do this: in Fig. 6 we use the **Clause 7** model of the **Guide** as an illustration.

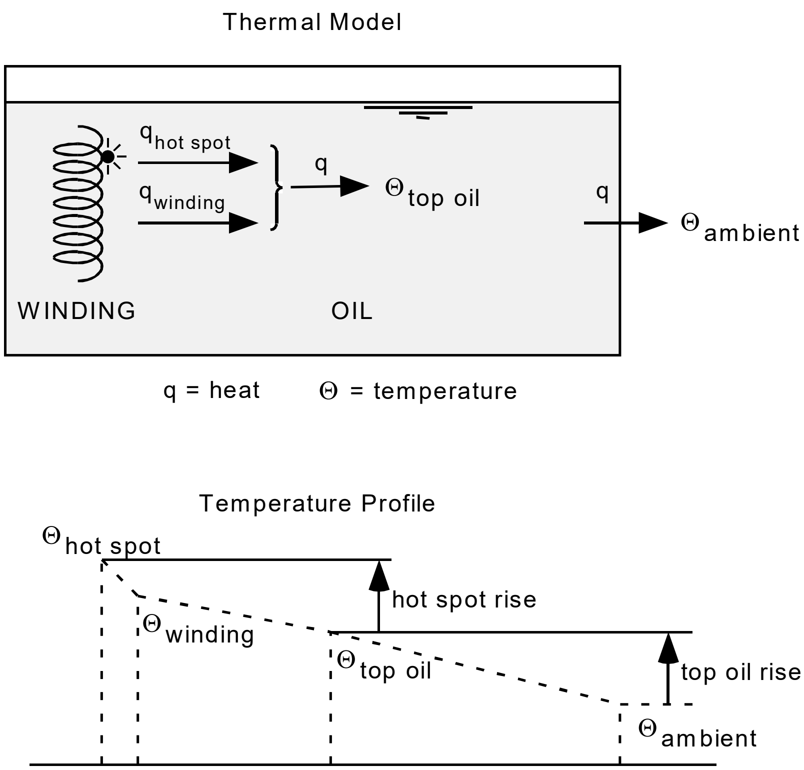

Fig. 6. The **Clause 7** model.

There is not universal agreement as to the “correct” model, and therefore some comments are in order:

a) Clause 7 of the IEEE Guide

The method recommended in this clause is the same as the one used in the old guide, C57.115-1991, which in turn is similar to the method of an earlier prior guide, C57.92.1981.

The *winding temperature*, Θ_{wdg} , is not used directly in the calculations, and the specific oil temperature used is the top oil temperature. In fact, the commonly-seen temperature gauges on large power transformers are often labeled

“Liquid Temperature” meaning measured top oil temperature, and

“Winding Temperature” meaning deduced hot spot temperature,

consistent with this approach.

b) Annex G of the IEEE Guide

The method recommended in this section of the **Guide** involves a more accurate approach, based directly on a model involving fundamental thermodynamic equations.

One difference is the use of the **heat** variable directly, rather than just “implied” as in Eq. (1). Another difference is in the use of two intermediate temperature variables: “duct oil temperature” and “temperature of oil adjacent to winding hot spot.” Also, the “top oil temperature” variable is eliminated in favor of the “bottom oil temperature.”

It is not practical here to discuss the **Annex G** method in detail. The reader instead should apply the equations given there, in mathematical form and in BASIC language form. Additional details are given in references [21] and [22].

c) IEC Standard 354:1991-09[24]

In this standard, the *hot spot temperature rise* is taken to be about 1.3 times the *average winding temperature rise* above the *average oil temperature*. The derivation of *average oil temperature* starts from a *bottom oil temperature* basis, which agree with part of the Annex G approach of the IEEE guide. On the other hand, the differential equation approach of the IEC Standard is quite similar to that of Clause 7 of the IEEE guide.

The Clause 7 equations, on the other hand are quite concise, and will therefore be discussed in the next section. However, it should be noted that given the limited accuracy of the Clause 7 equations, their application in transformer overload protection relays should be cautious and conservative, especially for suddenly applied moderate to severe overloads.

3. Equations for the Clause 7 Approach

These equations are based on the temperature profile assumption of Fig. 7. A modification to include the effect of ambient temperature variation is added, based on the assumption that *ambient temperature drives the oil temperature up and down with the same time constant as does the winding temperature*. Note that this is not a new idea here: it follows from the fact that when load drops to zero, the cooling effect is *driven* by the ambient temperature.

The equations, then, are:

$$\tau_{TO} \frac{d\Theta_{TO}}{dt} = \left[\Delta\Theta_{TO,U} + \Theta_A\right] - \Theta_{TO} \qquad (2)$$

$$\tau_H \frac{d\Delta\Theta_H}{dt} = \Delta\Theta_{H,U} - \Delta\Theta_H \qquad (3)$$

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R}\left[\frac{K^2 R + 1}{R + 1}\right]^n \qquad (4)$$

$$\Delta\Theta_{H,U} = \Delta\Theta_{H,R} K^{2m} \qquad (5)$$

Finally,

$$\Theta_H = \Theta_{TO} + \Delta\Theta_H \qquad (6)$$

Note there is a slight difference between these equations and the ones in the **Guide**: the ambient temperature variable Θ_A is moved from Eq. (6) to Eq. (2). With this change, it can vary as an arbitrary time function without violating the thermodynamic principles on which the original equations were based.

The symbols used are consistent with those of the **Guide**, and are re-defined here for convenience (all temperatures in degrees celsius):

Θ_A = ambient temperature
Θ_{TO} = top oil temperature
Θ_H = hot spot winding temperature
$\Delta\Theta_H$ = hot spot rise above top oil temperature
$\Delta\Theta_{TO,U}$ = ultimate top oil temperature rise
$\Delta\Theta_{TO,R}$ = rated top oil temperature rise over ambient
$\Delta\Theta_{H,U}$ = ultimate hot spot temperature rise over top oil (for a given load current)
$\Delta\Theta_{H,R}$ = rated hot spot temperature rise over top oil (for rated load current)
τ_{TO} = top oil rise time constant
τ_H = hot spot rise time constant
K = load current, per unit of the test MVA
R = ratio of rated-load loss to no-load loss at applicable tap position
m = empirically derived exponent, dependent on the cooling method, to "…approximately account for effects of changes in resistance and oil viscosity with changes in load."
n = empirically derived exponent, to "…approximately account for effects of change in resistance with change in load."

There are several approaches to the solution of these equations, using numerical methods. It is not part of this committee's function to delve into the mathematics of the solutions.

It is worth noting, however, that 'exponential responses,' are not the proper approach, especially when "m" and "n" are not unity, and that variable ambient temperature is incorporated easily into the equations as presented here.

4. Other considerations

In the application of transient heating equations, considerations related to the accuracy of the input data and the subsequent calculations within the relay become important during overloads since loss of life is an exponential function of hot spot temperature.

A justification for using a simple equation set is that refinements may not be justified in view of the expected error in input data.

Some of the possible other considerations follow.

a) Very-Low Ambient Temperatures

Table 4 in the **Guide** suggests loadability limits for temperatures ranging from -30ºC to +50ºC. In order to confirm these guidelines at the low end of the temperature range, since oil viscosity becomes a major factor, Aubin and Langhame performed some experimental work in 1992 [16], resulting in a new proposed model. Their results, which were for natural cooling only, showed that hot spot temperatures could be underestimated badly if the Clause 7 model of the **Guide** is extrapolated to ambient temperatures well below 0ºC.

For example, at an ambient temperature of -30ºC and 50% overload, the authors' model indicates a sudden hot spot rise to 95ºC, leveling out to 115ºC in the steady-state. The (extrapolated) Clause 7 approach indicates a sudden hot spot rise to 70ºC, leveling out to 110ºC in the steady-state. Of course none of these temperatures is in the severe insulation damage region, bearing in mind that rated hot spot temperature is usually 110ºC.

b) Correction of the Oil Time Constant (τ_{TO}) for heavy loadings and non-unity "n"

The top oil time constant is found experimentally by applying a step load change from zero to one per unit current, and deriving τ_{TO} from the initial slope of the exponential rise.

If n is not unity, the effective time constant is reduced for loads above one per unit, as illustrated by the example for the upper two curves of Fig. 7. For a step load change following an initial 55ºC rise, the time constant should be corrected from three hours to about two hours (upper curves). Equation (15) of the **Guide** defines how to make this correction, if desired. For this example, a compromise would be to use 2½ hours throughout, or 2 hours if overloading is the region of main interest.

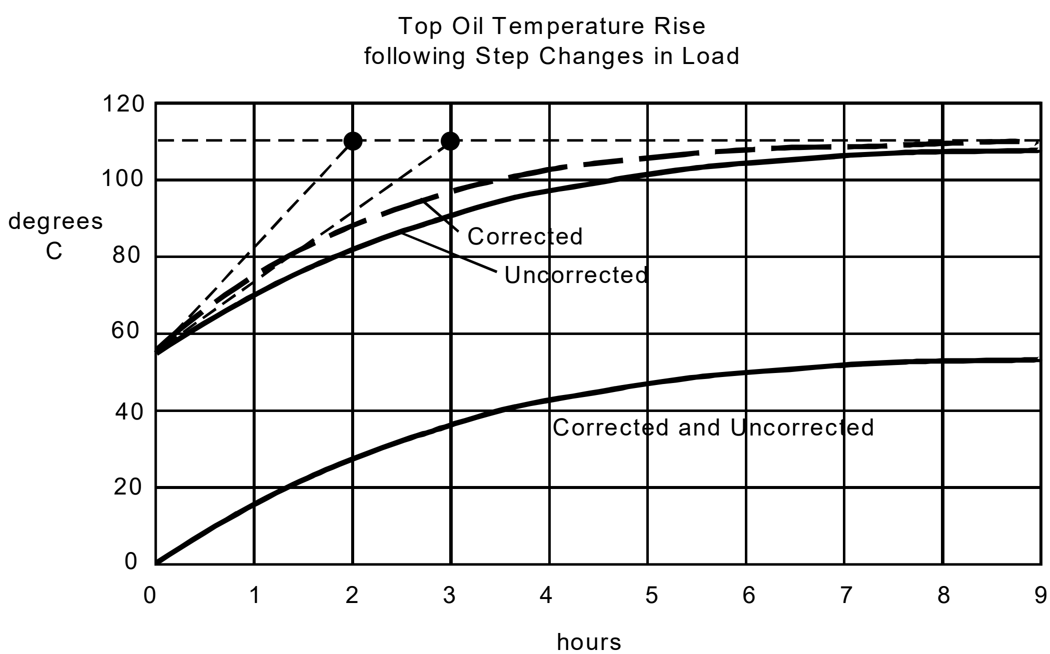

Fig. 7. Effect of corrections to the time constant, for n = 0.8 .

(For n = 1 there is no correction at any temperature level. Also, the time constants of 2 and 3 hrs are estimated by projecting the initial slopes into the final value line as shown.)

c) Winding Hot Spot Time Constant (τ_H)

In the **Guide**, there is a recommendation that the winding hot spot time constant be assumed zero (similar to the IEC Standard recommendation) since this is conservative "…for moderate overloads." This approach could however lead to a false alarm or false trip if the calculated *hot spot temperature* were used for alarm or tripping purposes, since this temperature would be over-estimated. In practice, this over-estimate is not likely to be a problem since this time constant is on the order of five to ten minutes.

It is interesting to note that the probe commonly used for measuring top oil or hot spot temperature has an inherent time constant of about three minutes. In other words, a hot spot time constant that appears to be seven minutes using the probe as a detector, will in reality be about four minutes![1]

There is an additional time constant for the thermal well used to simulate the hot spot temperature. On some forced oil transformers the thermal well time constant has been too long causing delayed starting of pumps during start up of the transformer. An IEEE Task Force of the IEEE Transformers Committee is investigating this problem and a report is planned.

d) Oil Viscosity and Winding Resistance

In the **Annex G** method, oil viscosity is taken into account in a more fundamental way.

The Institut de Researche d'Hydro-Quebec (IREQ) has produced a model that takes into account the increased oil viscosity (and hence reduced cooling effectiveness) for temperatures down to -40°C ambient. The study was limited to the natural oil circulation case, for which they found that the IEEE model "…can be used down to -20°C without any special modification to take account of oil-viscosity variations."

In the Clause 7 approach it is assumed that the effect of resistance change with temperature is cancelled by the effect of decreased viscosity with higher temperatures.

C. Implementation considerations

1. Required live inputs to the relay

a) Ambient Temperature

The ambient air temperature detector must be located far enough away from the transformer such that the heat being dissipated from the monitored transformer does not impact the ambient temperature measurement. Further, the detector should be designed such that it will not give incorrect air temperatures due to direct sun, wind, or rain conditions. If the adaptive thermal

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[1] Measurements carried out by G. Swift, June 1998.

overload relay can monitor wind speed and rain conditions for analysis purposes, then a weather station type device is required.

b) Transformer Loading

Loading inputs for adaptive thermal overload relays can range from high side or low side amperes to actual KVA. The loading input source may be determined by the need for load data for operating and planning purposes. If only ampere information is available, operating voltage assumptions or approximations will have to be programmed into the adaptive thermal overload relay. If actual KVA information is desired, then voltage transformers will be required. Load current and applied voltage inputs would be required for the calculation of load losses and no-load losses. Accuracy considerations will determine the need for single phase or three phase metering.

c) Top Oil Temperature

Many transformers have a temperature measuring element immersed in the top oil. This element is equipped with contacts to start cooling equipment and/or initiate an alarm. If top oil temperature input is required for an adaptive thermal overload relay, the existing top oil temperature device would have to be replaced with an appropriate transducer device or an additional transducer device installed.

d) Hot-Spot Temperature

Ideally, the best method to measure the hot spot winding temperature would be to measure the actual hot spot temperature with a transducer and sending that data via a fiber optic link to an adaptive thermal overload relay. However, this direct measurement technique cannot be practically retrofitted of existing transformers and it may not be a cost justified option on new transformers.

On existing transformers the most common method of measuring the hot spot winding temperature is simulating the hot spot temperature with a thermal relay responsive to both top oil temperature and to the direct heating effect of load current. The thermal relay element is immersed in the transformer top oil. An electric heating element is supplied with current proportional to the winding current. The thermal relay tracks the temperature of the hot spot of the winding during operation. This thermal relay is equipped with contacts to start cooling equipment and initiate alarms.

If the simulated hot spot winding temperature inputs are required for an adaptive thermal overload relay, the existing hot spot temperature device would have to be replaced with an appropriate transducer device or an additional hot spot winding temperature transducer device installed.

Electronic transformer hot spot winding temperature devices are available that need only one thermowell and sensor to measure the top oil temperature. The electronic unit utilizes an input load current measurement along with the top oil temperature measurement, to calculate the hot spot winding temperature. A present commercially available device of this nature has a <u>fixed</u> hot spot time constant of six minutes.

An adaptive thermal overload relay could use this <u>measured</u> top oil temperature, rather than <u>calculated</u> top oil temperature (using equation 4 in section B.3, part II).

e) Cooling Equipment

Most transformers, 138 kV and below, have a self cooled, oil and air (OA), type rating. These transformers may also have one or two stages of additional forced air (FA) and/or forced oil and air (FOA) cooling. The cooling equipment may be powered from a single AC source or from two AC sources with a throwover scheme. With OA type transformers, it is typical to alarm only, and not trip, for the loss of the AC source.

A transformer hot spot winding temperature thermal indicator is normally included with most transformers. This indicator typically has three individual, temperature settable contacts available. A contact from the transformer hot spot indicator is also typically used to automatically switch on a cooler group. For an FOA transformer, this indicator would typically add the second set of coolers as a result of increased hot spot temperature. An adaptive thermal overload relay may be able to more accurately control this process. The indicator contacts are also used to provide local alarming or input into SCADA.

Some EHV, 345kV and above, transformers have no self cooled rating. For these forced oil and air (FOA) type transformers, it is desirable to keep a set of coolers on at all times since damage can occur from high spot temperatures. EHV banks usually have two independent cooler groups powered from two independent AC sources. A multi-position selector switch is typically provided to control the cooler group usage.

A digital thermal relay, with programmable logic (PLC) type capability, could also provide the selection capability. It should also be noted that many EHV transformer banks are made up of three, single phase transformers and may have three sets of cooler controls. A cooler group can consist of a number of fans and pumps. It is common practice to trip EHV FOA banks off for loss of both the normal and standby AC sources to the cooling equipment. It is also common to initiate the trip after a specified time delay such as 15 minutes. An adaptive thermal overload relay could use the loss of AC, along with other information (e.g. hot spot, load, ambient temperature) to provide a more accurate trip/time requirement. The relay could also monitor individual fan and pumps to determine their working status (i.e. measure running current with donut ct's). This would require the relay to be designed with sufficient inputs/outputs and internal logic capability. Based on the number working, a real time transformer loadability could be calculated. It should be noted that the coolers are typically tripped off after a transformer fault. This action prevents possible increased fire risks including fanning the flames type of problems and this practice should continue.

Some older EHV transformers, equipped with an Inertaire Oil Preservation System, must be operated with a portion of the pumps running, without fans, for a cool down period following service. They also must run for a startup period prior to energization. This may require that the controls be designed to operate the fans and pumps separately and from different sources of power. Again, an adaptive thermal overload relay with PLC capability would be able to accommodate these control needs.

2. Functional Requirements

Hardware implementation of a stand alone transformer thermal protection relay is similar to any other digital protective relays. The relay hardware consists of a data acquisition system which includes interface for voltage, current, and temperature inputs, analog pre-filtering, analog multiplexing of input signals, and analog-to-digital conversion. The digital subsystem consists of microprocessor, memory, communications, digital input circuits for contact inputs, and digital output circuits for sending contact output signals.

The algorithms described in this paper can be implemented on the microprocessor technology available today. The response time requirements of the thermal protection algorithms are much slower compared to the differential protection of the transformer. The thermal protection algorithms described in this paper can easily be implemented on the same relay platform which is providing differential and other protection functions.

The load current and applied voltage information is required for the calculation of the I^2R and no-load losses respectively. The top oil temperature, ambient temperature, transformer losses, and cooling system status will be used to estimate the hot spot temperature. Based on this information, the loss of life can be estimated and proper adaptation to the overcurrent and other protective relay settings can be made. The main and auxiliary cooling system can be controlled. Also, load shedding schemes can be incorporated.

The above protection algorithm can also be implemented on the substation host computer if the voltage, current, temperature, and cooling system status is available through the communication network or substation local area network (LAN).

D. Additional Functions

As outlined in Section I.A.3 of this document, the expression “loss of life” means the loss of life of the *solid insulation* in the transformer, not the life of the whole transformer as such. However, since there is no accepted way of calculating the latter, *loss of insulation life* is often taken as a good indicator of *loss of transformer life*.

The equations in that section can be adapted to provide some additional functions:

1. Logging of the accumulated loss of life (= loss of life)

This function would provide an on-line integration of rate-of-loss-of-life (ROLOL) over time. This measurement may be used to schedule internal transformer inspections to evaluate operational integrity, to recalculate loadability, or to plan for unit replacement.

2. Prediction of planned or unplanned overload capacity

This prediction would be based on projection of the present value conditions of loading, ambient temperature and hot spot temperature, into the future. This is where the ‘normal’ rate of loss of life might be exceeded, for periods based on judgment, in accordance with Table 1. These pairs of values are simply the curve in Figure 2 of the **Guide**.

ROLOL relative to "NORMAL" (same as 'aging acceleration factor' F_{AA})	*Hot Spot Temperature °C*
1	110
2	117
4	124
8	131
16	139
32	147

Table 1 - Relationship between *Rate of Loss of Life* and *Hot Spot Temperature*

Note that the **Guide** says, "Operation at hottest-spot temperatures above 140°C may cause gassing in the solid insulation and the oil." This indicates that temporary operation at even 16 times normal rate of loss of life is reasonable, for short time overloads.

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