

FUNDAMENTAL PRINCIPLES OF TRANSFORMER THERMAL LOADING AND PROTECTION

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Abstract

Power transformers are traditionally protected by differential protection schemes that use voltages and currents to detect abnormalities in the differential zone of protection. For this type of scheme, a short circuit or high magnitude current must be present to initiate a trip. However, this scheme might not be ideal when transformers need to be overloaded to mitigate contingency conditions. Using the IEEE Guide for Loading of Oil-Immersed Power Transformers C57.91-1995, one can thermally rate transformers beyond their nameplate conditions to a level that is safe for operation. Using the guide, engineers can establish continuous, emergency and short term emergency transformer ratings. Operators can use these ratings until the contingency conditions are mitigated. However, once the transformer has surpassed the short term emergency ratings, the transformer might reach critical temperatures and could possibly sustain damage. Protection engineers can avoid further transformer damage by using the thermal protection principles of the IEEE standard. This paper discusses the fundamental thermal principles of power transformers, philosophies of operations and the implementations of thermal protection.

Introduction

Transformer overloads can occur during contingency conditions that are the product of one, two, or various system elements being isolated from the power the system. They can also occur when transformers are already at 80%-90% of their full nameplate rating and extra capacity is needed, especially during hot summers. Depending on a utility's criteria, transformers may be allowed to be overloaded, while still maintaining transformer integrity, to keep continuity of the load for economical or reliability reasons. To make these decisions intelligently, we must comprehend the thermal effects that oil and winding temperatures have on the life of insulation.

The no-load and load-losses created by the transformer core and windings will generate high temperatures that, if not controlled in a timely manner, can damage the dielectric properties of the insulation. During normal operating conditions, the temperature thermal process is controlled by the cooling system that keeps the transformer in a thermal equilibrium. Transformer manufacturers guarantee the longevity of their product as long as it is operated under the temperature specifications of IEEE or IEC standards. What if transformers need to be loaded beyond normal conditions? How would the standards help us in this case?

The IEEE Guide of Loading of Mineral Oil-Immerse Transformers C57.91-1995 aids us in calculating the effect of aging insulation and its exposure to high temperatures. The guide also leads us through the calculation of the winding hottest-spot temperature, which is the driving factor for limiting temperature overloads. Knowing how to calculate the loss of life and the winding hottest-spot temperature is the foundation for the development of dynamic ratings for power transformers. Such ratings can be used by system operators during contingency conditions, which will allow them to overload transformers for a predetermined time.

Transformer dynamic ratings can also be used to create settings criteria for thermal relays. New numerical relays are capable of replicating the thermal model outlined by the IEEE guide, and the relay engineer can set thermal limits based on the dynamic ratings established by the loss of life of insulation and winding hottest-spot calculations. In addition, some thermal relays can predict future temperature states based on constant present values. Such concepts can alarm system operators 15 to 30 mins in advance of a temperature limit violation in the transformer, giving them time to mitigate problems. In order to properly apply thermal protection for the power transformer, a clear understanding of thermal aspects during overloads is necessary. We must understand the causes for heat, the normal operation limitations, the insulation's loss of life and the hottest-spot temperature; we must also develop philosophies and criteria for transformer dynamics ratings.

Transformer Basics: What Affects Thermal Loading

Most professionals in the power industry are very familiar with the fundamental principle of how a transformer functions electrically. A transformer is a voltage changing device composed of a primary and secondary winding interlinked by a magnetic core (10). A three phase power transformer used in transmission and distribution systems shares the same principle. However, its core is bigger to accommodate the three phase primary and secondary windings. Additionally, insulation in the

form of oil or paper is required to isolate the difference in potential between phases. Three phase transformer losses will generate enough heat so that external cooling systems must be added. A closer look at these characteristics is necessary to better understand the thermal aspects of power transformers.

The Core and Windings

When one thinks of a transformer core, one usually visualizes it as a piece of solid metal. On the contrary, the core is built up by horizontally or vertically stacking thin iron laminations or sheets, which eventually form the core's leg and yoke, as seen in **Figure 1** (5). The primary function of the transformer core is to provide a low reluctance path for the flux that links the primary and secondary windings. Ideally, we would like a zero reluctance flux path between the two windings. However, due to the iron laminations that form the core, the transformer core experiences losses that eventually produce heat. These core losses can be classified as hysteresis and eddy current losses. See the section on transformer losses, below, for further details.

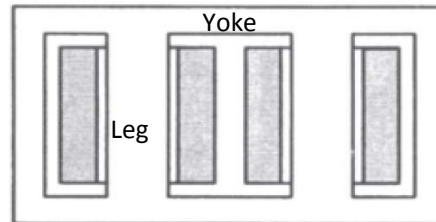


Figure 1. Three Phase Transformer Core.

Insulation

Insulation is required whenever there is a difference in potential between two points (7). In an overhead three phase transmission line with bare conductors, no insulation is necessary between the conductors since air separation is used as an insulator, preventing the flow of current. However, in power transformers, distance between phase conductors is not an efficient way of separating the potential differences. As a result, paper is used as an insulator, allowing closer proximity between phases and thus maximizing space. By far, paper is the best insulating material used today because of its high dielectric strength properties (10). Paper insulation in a power transformer is installed between windings of the same phase, windings to ground, and windings from different phases (7). Other parts of the transformer also experience a difference in potential, such as the transformer tank wall with the windings, which also requires some form of insulation. In order to minimize the transformer's footprint, this distance must be shortened as much as possible. Transformer manufacturers shorten the necessary distance by using insulating oil, which not only insulates, but also serves as a coolant within the transformer (5). Thus, transformer insulation is the heart of transformer design, and maximum transformer performance during loading depends on the insulation's credibility. Transformer losses are one of the primary factors affecting this credibility, which is the focus of the next section.

Transformer Losses

Even though transformers are very efficient devices, converting from 95-99% of their input power, some of its energy is lost during the voltage transformation (10). The losses in a power transformer can be classified as no-load losses and load losses.

No-Load Losses. With no load in the secondary windings, an energized transformer behaves as a highly inductive element, similar to a shunt reactor. In order to keep this transformer energized, the alternating excitation current is drawn from the system, producing an alternating mutual flux in the primary winding. This mutual flux is taken by the core at a rate that depends on the system frequency. The energy requirements for this cyclic magnetization of the core results in two types of transformer losses: eddy and hysteresis losses. Induced voltage in the laminations produced by the alternating flux results in undesirable currents within the laminations. Such currents are called eddy currents, which do not contribute to power output, and their energy is lost to heat (10). The alternating magnetization of the core will cause the molecular composition of the iron core to align itself with the changing field. The energy lost from successive reversal of magnetization in the core is called hysteresis loss (4).

Load Losses. The load losses in a power transformer are due to the electric resistance of windings and stray losses. The resistive action of the winding conductor to the current flow will be lost in the form of heat and will be dissipated in the surrounding area inside the transformer. The magnitude of that loss increases by the square of the current I^2R . Stray losses occur due to the leakage field of winding and due to high currents seen in internal structural parts such as bus bars. Stray losses can affect the overall rating of the transformer because they can create hot spots when the current leads become excessive, affecting the overall life of the transformer (10).

Heat Transfer Effects

A load serving transformer not only experiences an electrical process but also goes through a thermal process that is driven by heat. The heat generated by the no-load and load losses is the main source of temperature rise in the transformer. However, the I^2R losses of the windings and stray losses seen from the structural parts are the main factors of heat generation within the transformer. The thermal energy produced by the windings is transferred to the winding insulation and consequently to the oil and transformer walls. This process will continue until an equilibrium state is reached when the heat generated by the windings equals the heat taken away by some form of coolant or cooling system (4). This heat transfer mechanism must not allow the core, windings, or any structural parts to reach critical temperatures that could possibly deteriorate the credibility of the winding insulation. The dielectric insulating properties of the insulation can be weakened if temperatures above the limiting values are permitted (10). As a result, the insulation ages more rapidly, reducing its normal life. According to the IEEE C57.91-1995 guide, the life of the insulation is the overall life of a transformer (8).

Due to the temperature requirements of the insulation, transformers utilize cooling systems to control the temperature rise. The best method of absorbing heat from the windings, core, and structural parts in larger power transformers is to use oil (5). As we will see in the next sections, the oil's heat capacity and thermal conductivity affect the heat transfer process.

For smaller oil-field transformers, the tank surface is used to dissipate heat to the atmosphere. For larger transformers, heat exchangers, such as radiators, usually mounted beside the tank, are employed to cool the oil. The IEEE C57.12.00-2000 standard identifies the type of cooling system according to **Table 1**.

Table 1. Transformer Cooling Types.

Cooling Class	Definition
ONAN	Oil Natural-Air Natural
ONAF	Oil Natural-Air Force
OFAF	Oil Force-Air Force
OFOD	Oil Force-Oil Directed

ONAN refers to the dissipation of heat from the oil to the atmosphere. This is done by the natural circulation of the oil through the windings and cooling equipment, which is externally cooled by natural air. As the temperature of the oil rises due to the active parts of the transformer, the specific gravity of the oil decreases, causing the oil to travel upwards towards the inlet of the coolers. As the oil travels through the heat exchangers or coolers, its specific gravity increases, allowing it to flow downwards. This natural circulation of the oil is due to the gravitational buoyancy in the cooling system loop (10). See **Figure 2a**.

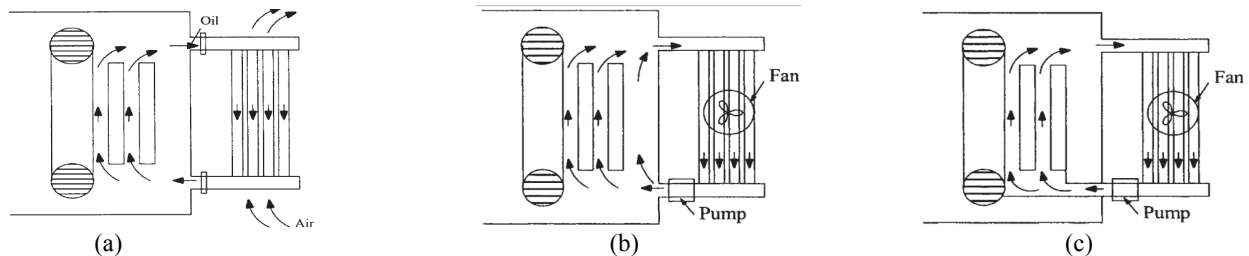


Figure 2. Transformer Cooling Types (a) ONAN, (b) OFAF, (c) ODAF.

The ONAF cooling designation maintains the natural circulation of oil through the windings and heat exchanger, except that air is now forced to the surface of the radiators. As load increases, the previous natural cooling process is no longer enough to dissipate the heat at a rate that can keep the temperature of the transformer in equilibrium. If fans are used to cool down the radiators, the heat transfer process will be increased, resulting in additional transformer capacity (10). A transformer rating of up to 133% of the base rating can be achieved by adding one stage of fans and up to 167% with two stages (1).

The OFAF cooling designation increases the heat transfer rate by forcing oil circulation with pumps. To achieve maximum heat dissipation under OFAF cooling, fans must continually blow air on the surface of the radiators (10). See **Figure 2b**. A better way to improve heat dissipation is to force oil through the winding as shown in **Figure 2c**. When oil is forced to flow through the windings, it is indicated as Directed Flow and its designation is ODAF. When the oil is forced to flow freely inside the tank it is indicated to be Non-Directed flow. See **Figure 2b**.

A transformer's thermal process is controlled by keeping its temperature under the permitted values indicated by the manufacture. These limits are usually set by following IEEE or IEC industry standards for power transformers.

IEEE Standards and Temperatures

In order to operate a power transformer, one must know its basic limitations. It is clear that the temperature produced by the transformer losses can affect the life span of the insulation. To ensure the longevity of the transformer, transformer manufactures must guarantee that their designs are capable of operating within specified standards. But what are the guaranteed temperature limits stated by the standards? The operating limits are bounded by the ambient temperature, the average winding temperature, and the maximum winding hottest-spot temperature.

According to the IEEE C57.12.00-2000 standard, power transformer are rated on a maximum ambient temperature of 40° C, and the average ambient temperature shall not exceed 30° C in a 24-hour period. This standard also states that an average winding rise of 65° C shall not be exceeded when the transformer is operated at its rated load (KVA), voltage (V), and frequency (Hz). In other words, based on the ambient temperature criteria, the average temperature of the winding cannot exceed 65° C above ambient, when operated at rated conditions.

Maximum hottest-spot winding temperature cannot exceed a value of 80° C above ambient. The IEEE C57.91-1995 states that under a continuous ambient temperature of 30° C, the maximum hottest-spot winding temperature should not exceed 110° C. If the transformer is operated continuously at this temperature, the normal life expectancy of the transformer is 20.55 years (8). In this section, we've described temperature limitations under rated conditions. But what happens when transformers need to be loaded beyond nameplate ratings? That is the focus of the next section.

Loading Transformers Beyond Nameplate Rating

There are different reasons why transformers become overloaded, or why utilities may choose to overload them beyond their nameplate ratings. One reason is because the load demand has caught up or surpassed the transformer capacity and additional capacity is needed. Due to the complexity and exposure of the power system, no matter how well it is designed, failures are going to occur. It is the primary function of protective equipment to recognize such faults and isolate the faulted element from the rest of the system. This will cause the power flow to find new ways to reach the load demand. Transformers that find themselves on such paths might experience overloads beyond their normal capacity. In fact, depending on economical and reliability reasons, it may be necessary to overload transformers to use 25%, 50%, or more of their transformer life to maintain customers' loads or to give system operators time to mitigate contingency conditions and prevent a potential blackout. It is possible to intelligently overload transformers to a rating that is still safe to operate by using the IEEE guide for loading of mineral-oil transformers C57.91-1995. The guide outlines the risks, theory, and calculations that make it possible to overload power transformers. Understanding the aging of the insulation and how to calculate the hottest-spot winding temperature are of vital importance in order to know how much a transformer can be safely overloaded.

Aging of Insulation

A power transformer's solid insulation has two essential characteristics: dielectric strength and mechanical strength. Dielectric strength is maintained until the insulation is exposed to certain elevated temperatures. At that point, the insulation also becomes brittle and loses its mechanical strength (10). If the elevated temperatures are severe, the insulation will no longer be able to maintain its properties, resulting in insulation failure and ending the useful life of the transformer. Side effects of insulation aging include the formation of water and oxygen (11). However, with new oil preservation systems, these formations can be minimized, leaving the insulation temperature exposure as the controlling parameter for control personnel (8).

In the late 1940's, it was discovered that the aging of insulation is part of a chemical process. Its reactions vary with temperature according to the Arrhenius equation.

$$Ko = Ae^{(B/(\theta+273))}$$

The IEEE standard C57.91-1995 translates this equation on a per unit life basis indicated by the curve in **Figure 5**.

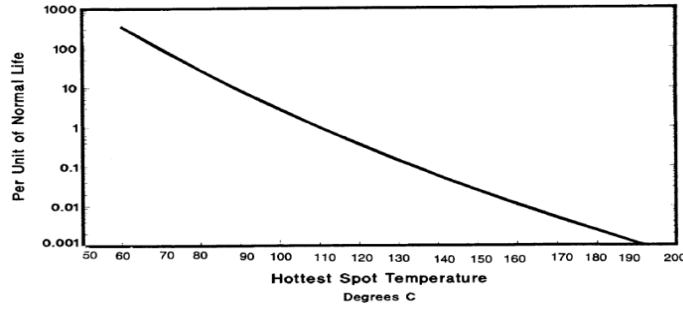


Figure 5. Transformer Insulation Life.

The curve indicates that if the winding hottest-spot temperature is allowed to go beyond 110° C, the age of the insulation is accelerated above its normal rate and decelerated for temperatures below 110° C. Transformers with loading factors between 55% and 65% might seldom reached this temperature, resulting in slow insulation aging.

The equation for per unit life curve is shown below:

$$\text{Per Unit Life} = 9.80 \times 10^{-18} e^{[15000/(\Theta H + 273)]}$$

The 15000 constant value corresponds to the slope of aging and represents most forms of insulation. ΘH is the hottest-spot winding temperature. This per unit life equation is the basis for calculating the aging accelerating factor curve in **Figure 6**.

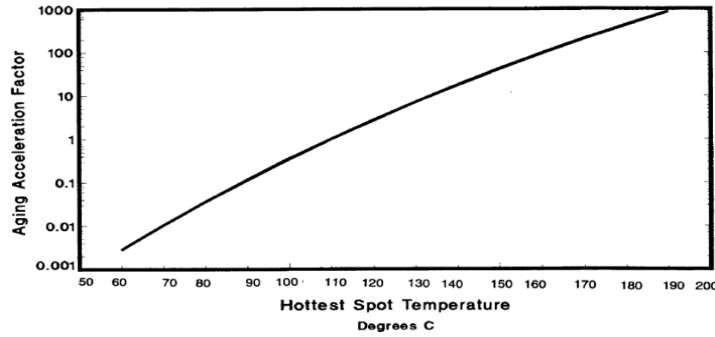


Figure 6. Aging Accelerator Factor.

The aging accelerating factor is calculated using the following equation:

$$FAA = \left[\frac{15000}{383} - \frac{15000}{\Theta H + 273} \right]$$

The aging accelerating factor can be used to calculate the life of a transformer for a predetermined hottest-spot winding temperature. However, to calculate the loss of life of a transformer for a 24-hour cycle, we must use the following equation:

$$FEQA = \frac{[\sum_{n=1}^N FAAn * \Delta tn]}{\sum_{n=1}^N \Delta tn}$$

Where:

- FEQA Equivalent aging factor for the total time period
- N Total number of intervals
- n Index of time interval
- FAAn Aging accelerating factor at index n
- Δtn Time interval

A transformer's total loss of life can be derived as a percentage by using the following equation:

$$FEQA = \frac{FEQA * t * 100}{Normal\ Life\ of\ Insulation}$$

According to the IEEE C57.91-1995 guide, the length of insulation's normal life has been a topic of controversy for decades. Earlier versions of the IEEE C57.91- 1981 settled on an insulation life of 65000 hours for power transformers. The standard now states that this value might be extremely conservative; an insulation life of 180000 hours has now been used for many years.

This section has described transformer insulation's normal life, and factors that affect its aging. We also established that insulation's aging is directly connected with the hottest-spot winding temperature. If we are to establish a thermal overload rating, the hottest-spot winding temperature must be known.

The Winding Hottest-Spot Temperature

As it was determined before, an insulation's mechanical and dielectric properties are deteriorated at temperatures above normal limits. From the previous section, we now know that if the hottest-spot temperature is allowed to go beyond 110° C, the insulation deteriorates at a faster rate than normal. Therefore, the highest temperatures in the transformer aid in calculating insulation integrity.

The winding hottest-spot temperature is given by:

$$\Theta H = \Theta A + \Delta \Theta TO + \Delta \Theta H$$

Where:

- ΘA Ambient temperature
- $\Delta \Theta TO$ Top-oil rise over ambient temperature in ° C
- $\Delta \Theta H$ Winding hottest-spot rise over top-oil temperature

Ambient Temperature ΘA

To predict an overload for a 24-hour period, discrete 1-hour ambient temperature increments are necessary. The temperature used should be the maximum daily temperature for the month of interest averaged over several years.

Top-Oil Rise over Ambient Temperature $\Delta \Theta TO$

As explained in the thermal heat transfer process section, the heat produced by the core, structural parts, and winding of the transformer decreases the specific gravity of the oil, causing it to travel upward toward the top of the tank. During steady state load conditions, the top-oil rise over the ambient may be constant. On the other hand, under transient conditions or when the load increases or decreases, the top-oil rise over the ambient may be continuously changing (2). As a result of such behavior, the top-oil rise over the ambient is given by the following formula:

$$\Delta \Theta TO = (\Delta \Theta TO, u - \Delta \Theta TO, i) * \left(1 - e^{-\left(\frac{t}{\tau \Delta \Theta}\right)}\right) + \Delta \Theta TO, i$$

- $\Delta \Theta TO, u$ Ultimate top-oil rise over ambient temperature in °C
- $\Delta \Theta TO, i$ Initial top-oil rise over ambient temperature in °C
- t Duration of changed load in hours
- τ Thermal time constant for the transformer (accounting for the new load, and accounting for the specific temperature differential between the ultimate oil rise and the initial oil rise)

During a load increase or decrease, a heating transient occurs inside the transformer, causing the temperature to either go up or down. Due to transformer's large mass, it takes time for the heat to dissipate from an initial value to an ultimate value. Therefore, the initial ($\Delta \Theta TO, i$) and ultimate ($\Delta \Theta TO, u$) top-oil rises over the ambient formulas are given below:

$$\Delta \Theta TO, i = \Delta \Theta TO, R \left(\frac{Ki^2 R + 1}{R + 1} \right)^n$$

$$\Delta\theta_{TO,u} = \Delta\theta_{TO,R} \left(\frac{Ku^2R + 1}{R + 1} \right)^n$$

$\Delta\theta_{TO,R}$	Top-oil rise over ambient at full load (determined during test report)
K	Ratio of load of interest to rated load
R	Ratio of load loss at rated load to no-load loss
n	Empirically derived exponent used to calculate the variations of $\Delta\theta_{TO}$ with changes in load. Transformers with different cooling modes will have different n values, which approximate effects of change in resistance with changing load.

The time required for the top-oil temperature to reach its ultimate value is a function of the thermal oil time constant τ . The oil time constant for the top-oil rise is given below:

$$\tau_{TO} = \tau_{TO,R} * \frac{\left(\frac{\Delta\theta_{TO,u}}{\Delta\theta_{TO,R}} \right) - \left(\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}} \right)}{\left(\left(\frac{\Delta\theta_{TO,u}}{\Delta\theta_{TO,R}} \right)^{\left(\frac{1}{n} \right)} - \left(\left(\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}} \right)^{\left(\frac{1}{n} \right)} \right) \right)}$$

Where:

$$\tau_{TO,R} = \frac{C * \Delta\theta_{TO,R}}{PT,R}$$

$\tau_{TO,R}$	Oil time constant at rated load beginning with the initial top-oil temperature rise at 0° C
PT,R	Total power loss t rated load
C	Thermal capacity of the power transformer (watt-hour per °C) “The thermal capacity is the heat transfer to a unit quantity of matter in a body which will cause 1° C change in the temperature of the body” (2). Such thermal capacity will depend on the cooling system employed and size of the transformer.

The thermal capacity is calculated as follows:

For ONAN, ONAF cooling modes:

$$C = 0.06 * (\text{weight of core and coils}) + 0.04 * (\text{weight of tank and fittings}) + 1.33 * (\text{gallons of oil})$$

For OFAF cooling modes, either directed or undirected:

$$C = 0.06 * (\text{weight of core and coils}) + 0.06 * (\text{weight of tank and fittings}) + 1.93 * (\text{gallons of oil})$$

Winding Hot-Spot Rise over Top-Oil Temperature $\Delta\theta_H$

During a continuous or steady state load, the I^2R losses cause the temperature of the winding to increase. As the process continues, the heat is transferred to the surrounding oil. This heat transfer process continues until the heat generated by the windings equals the heat taken away by the oil under continuous load. During heat transient conditions, the winding hottest-spot rise may change from an initial value to an ultimate value depending on the winding hottest-spot time constant τ_w . This is given by:

$$\Delta\theta_H = (\Delta\theta_{H,u} - \Delta\theta_{H,i}) * \left(1 - e^{-\left(\frac{t}{\tau_w} \right)} \right) + \Delta\theta_{H,i}$$

$$\Delta\theta_{H,i} = \Delta\theta_{H,R} (Ki^{2m})$$

$$\Delta\theta_{H,u} = \Delta\theta_{H,R} (Ku^{2m})$$

$$\Delta\theta_{H,R} = \Delta\theta \frac{H}{A,R} - \Delta\theta_{TO,R}$$

Where:

$\Delta\theta_{H,i}$	Initial hot-spot rise over top-oil
$\Delta\theta_{H,u}$	Ultimate hot-spot rise over top-oil

$\Delta\Theta_{H,R}$	Winding hot-spot rise over top-oil
$\Delta\Theta_{H/A,R}$	Winding hot-spot rise over ambient
τ	Winding time constant
m	Empirically derived exponent to account for conductor insulation wall thickness, conductor configuration, oil viscosity, oil velocity, cooling mode

$\Delta\Theta_{H/A,R}$ is a value that is determined during manufacturing of the power transformer. The C57.91-1995 also recommends assuming a value of 80 °C for a 65 °C average winding rise and a value of 65 °C for a 55 °C average winding rise on its nameplate, respectively.

Our initial goal was to determine how much overload an oil-immersed transformer can sustain without severely affecting its integrity and knowing that it is still safe to operate. We described in previous sections that the driving factor for insulation credibility is temperature exposure, since at high temperatures insulation can lose its insulation properties. For this reason, it is necessary to establish the hottest-spot winding temperature. If we know the maximum hottest-spot temperature to which the insulation is exposed, we know how much life is lost, allowing us to limit the overload. For practical applications, following the formulas outlined above can be cumbersome, complex, and time-consuming. It will be explained in this paper's last section that a microprocessor protective relay can perform the algorithm calculations we have outlined, simplifying the job of calculation and application. However, the relay will require the user to input the maximum hottest-spot temperature where he/she wants the relay to operate. Computer programs can also facilitate the offline analysis and studies that are needed to establish limited ratings. As a result, rating methodologies can be created and refined.

Transformer Dynamic Ratings

Under the new North American Electric Reliability Corporation (NERC) standards for rating of power system elements, many utilities have implemented rating methodologies for power transformers. Rating methodologies are bounded by individual utilities' philosophies or criteria and their willingness to sacrifice transformer loss of life. Based on a rating philosophy and the calculations per IEEE C57.91-1995 outlined in this paper, utilities can create thermal dynamic ratings for power transformers. These thermal dynamic ratings can be utilized to set thermal relays, and they can also be applied to real time operating cases for system operators. Regardless of the philosophy employed, rating methodologies have dynamic ratings for four different types of loadings:

- Normal life expectancy loading
- Planned loading beyond nameplate
- Long time emergency loading
- Short time emergency loading

Normal Life Expectancy Loading

This type of loading states that the insulation ages at a normal rate over the life of the transformer. As stated previously, the total normal life of the insulation is established at 180000 hours, which equals 22.55 years. The normal life length assumes that the transformer operates at a continuous 30 °C average ambient temperature and a hottest-spot winding temperature of 110 °C. In-service transformers will seldom reach this temperature unless they are at full capacity or during testing conditions. This results in prolonging the life of the transformer. A 24-hour normal load cycle is shown in **Figure 6** where the ambient, top-oil, and winding hottest-spot temperatures are superimposed with the loading profile.

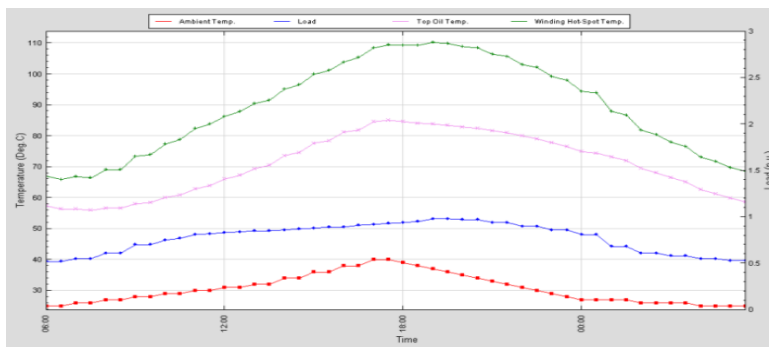


Figure 6. Transformer Normal Loading.

Planned Loading beyond Nameplate Rating

Figure 7 shows a transformer being overloaded beyond its normal capacity with winding hottest-spot temperature of 110 °C through 130 °C. Loss of life calculations should be used to determine the length of time that the transformer can be exposed to the indicated temperature range.

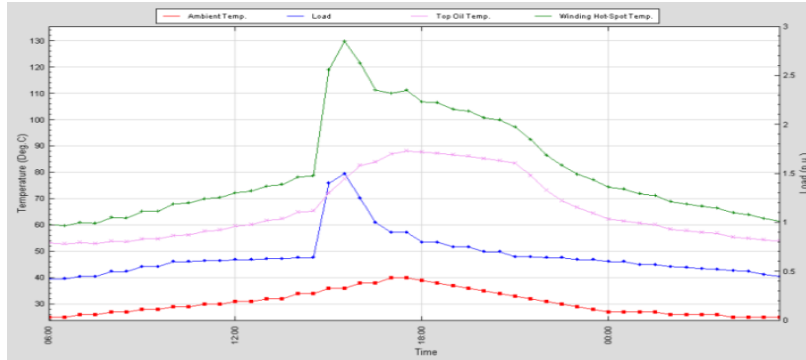


Figure 7. Transformer Planned Overload.

Long Time Emergency Rating

This rating is designed for single contingency conditions that can cause the hottest-spot temperature of the transformer to reach the range of 130 °C through 140 °C, as in **Figure 8**. The transformer can be exposed to these temperatures two or three times over the normal life of the transformer, and exposures can last several months. Loss of life calculations should be made to determine if the sacrifice is acceptable for the loading cycle.

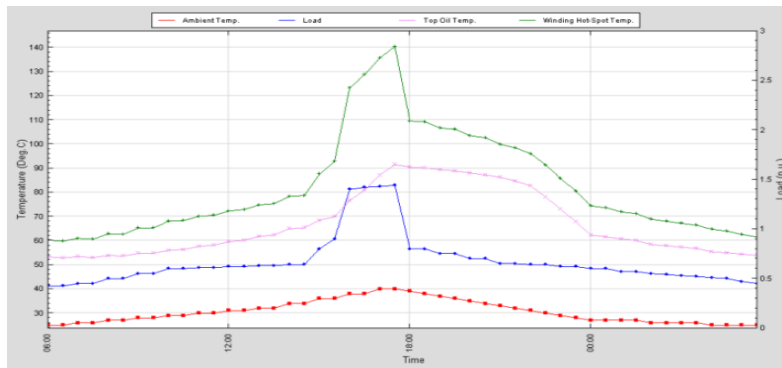


Figure 8. Transformer Long Time Emergency Loading.

Short Time Emergency Ratings

This type of rating is utilized for 2nd and 3rd contingency problems, and it allows transformers to carry very heavy overloads. The hottest-spot temperature should not be allowed to go beyond 180 °C, and such occurrences should be limited to one or two times over the normal life of the transformer. See **Figure 9**.

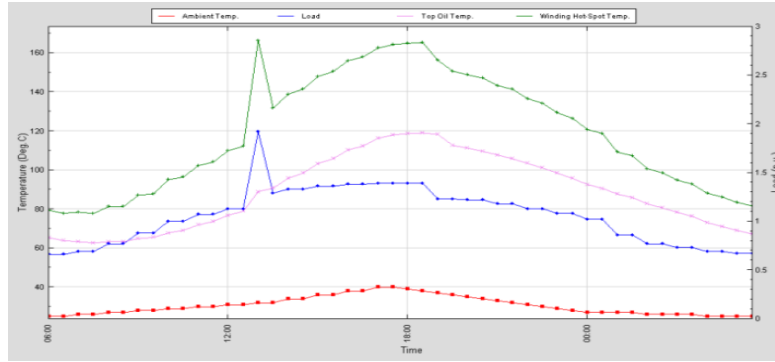


Figure 9. Transformer Short Time Emergency Loading.

Table 1 shows the recommended temperature limits for each type of loading for power transformers with an average winding rise of 65 °C, as per test reports or nameplate information.

Table 2. Maximum Temperature Limits for Types of Loadings.

	Normal loading	Planned loading	Long-time emergency loading	Short-time emergency loading
Hottest-spot winding temperature in °C	120	130	140	180
Top-oil temperature in °C	110	110	110	110
Maximum loading in %	200	200	200	200

Limitations

It is important to point out that there are risks involved when loading transformers beyond nameplate ratings. For example, the IEEE C57.91-1995 guide mentions that when operating a transformer beyond 140 °C, gas can form that may affect the integrity of the insulation. The standard contains more information on the effects of loading transformers beyond their nameplate ratings. The reader is encouraged to become familiar with these risk concepts.

Thermal Model Applied to Microprocessor Relays

The IEEE C57.91-1995 guide has given us the fundamental principles of power transformer thermal loading, which we have already established in previous sections. Many numerical transformer protection relays available today include thermal protection functions that replicate the theory behind the IEEE guide. An example of a microprocessor relay that can easily apply this thermal model is shown below. The 49 thermal function of this relay operates on measured or calculated top-oil temperatures and a calculated hottest-spot winding temperature. In addition, this relay can predict the hottest-spot winding temperatures into the future (minutes or hours). As a result, it can forecast temperature limit violations and loss of life. Such violations can then be sent to system operators as an early warning system.

Requirements

Applying thermal protection for a power transformer requires information that is readily available, so that implementation is a simple process. The relay algorithm requires nameplate data, as well as measurements of current, ambient temperature and top-oil temperature. If the top-oil temperature is not available, the relay can estimate it with great accuracy based on the nameplate data specifications, the real time current, and the ambient temperature. The physical requirements are shown in **Figure 10**.

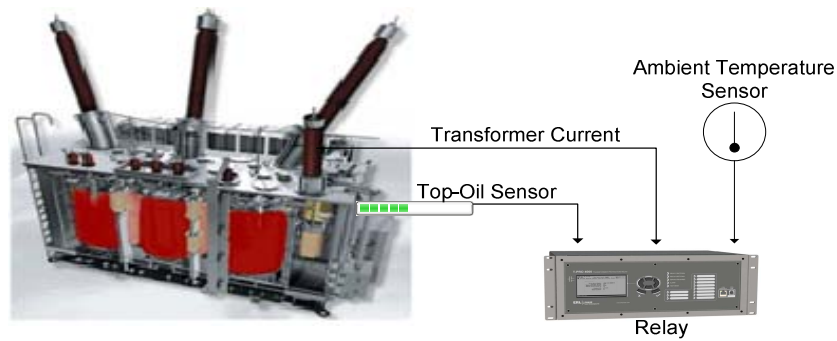


Figure 10. Physical Requirements for Thermal Protection.

The nameplate data is vital since it contains the type of cooling available and the temperature rise (65 °C or 55°C) of the transformer. The user can specify the type of cooling employed in the transformer, which tells the algorithm what thermal constants to choose. It is also possible for the user to modify the cooling characteristic constants if desired. The requirements for nameplate data are shown in **Figure 11**.

Nameplate Data		
Transformer 3 Phase Capacity (1-2000 MVA)	100.0	Maximum Transformer Rating
Transformer Windings	3	
Tap Changer Range	0 %	
Normal Loss of Life Hot Spot Temperature	110.0 °C	
Note: IEEE Standard: 110°C for 65°C rise trf, 95°C for 55°C rise trf.		
Transformer Temperature Rise	65 °C	
Transformer Cooling Method	Forced air cooled (O/A/F/A) rated 133% or less of self-cooled rating	
Temp. Rise Hot Spot (TriseHS)	30.00 °C	
Temp. Rise Top Oil (TriseTop)	50.00 °C	
Temp. Time Const. Hot Spot (TauHS)	0.08 hours	
Temp. Time Const. Top Oil (TauTop)	2.00 hours	
Ratio of Load Loss to Iron Loss (R)	4.50	
Hot Spot Temp. Exponent (m)	0.80	
Top Oil Temp. Exponent (n)	0.90	

Figure 11. Transformer Nameplate Information.

The relay requires three types of physical connections for the thermal algorithm:

- Top-oil temperature
- Ambient temperature
- Current

Top-oil sensors are usually already installed during the manufacturing process as part of their cooling. The relay's input requires a 4-20 ma signal from the RTD. This can be achieved by using a transducer capable of such output. The relay provides 30V DC voltages to power the transducer. If measuring the top-oil temperature is not possible, the relay is capable of calculating the top-oil temperature with great accuracy.

An ambient temperature sensor is also required for the thermal calculations. This sensor has to be in the proximity of the transformer being protected. The input of the relay requires a 4-20 ma signal from the ambient sensor or transducer, which can be powered by the 30V DC source of the relay.

If the thermal protection algorithm has been implemented in conjunction with a transformer differential function of the relay, then the transformer currents should already be available. If the relay is to be used as a thermal protection only, then the transformer currents must be connected to let the thermal algorithm know about load conditions.

Thermal Protection Using the 49 Function

A 49 thermal protection function can be implemented to make decisions based on top-oil temperature or winding hottest-spot temperature limits. The 49 function includes 12 stages of settings that could be used to issue alarms when the transformer is 80-90% loaded or to issue tripping decisions when the transformer has reached temperature limits. Such settings are shown in **Figure 12** along with their internal logic.

49-Thermal Overload												
	1	2	3	4	5	6	7	8	9	10	11	12
Current Input Switch												
Pickup (On)	OFF	1.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hysteresis (On)	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pickup Delay (T _{p1} , s)	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dropout Delay (T _{d1} , s)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Temperature Input Switch												
Pickup (On)	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Hysteresis (On)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pickup Delay (T _{p2} , hours)	0.01	0.02	0.03	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dropout Delay (T _{d2} , hours)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Logic Gate Switch												
LED Switch	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
LED Switch	Target	Target	Target	Alarm	Alarm	Alarm	Alarm	Alarm	Alarm	Alarm	Alarm	Alarm

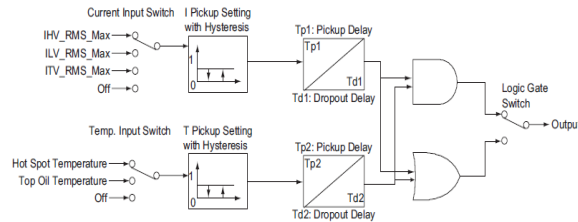


Figure 12. Thermal Protection Function 49 and Internal Logic.

Transformer Overload Early Warning System TOEWS

The transformer overload early warning system calculates the future hottest-spot temperature based on present temperature and load conditions. This predictive functionality of the relay can calculate the hottest-spot temperature for a specified amount of time in the future if present ambient temperature and load profiles are kept constant. The advantage of such system is to warn system operators in advance that a temperature limit will be reached and action is required. The system predicts excessive winding hottest-spot temperature for 15 or 30 min intervals in advanced. As a result, system operators have the necessary time to restore the loading pattern and alleviate the load of the transformer in question. **Figure 13** depicts possible temperature limits using the TOEWS.

TOEWS - Transformer Overload Early Warning System	
THS (Temperature Hot Spot) Trip Setting:	<input checked="" type="checkbox"/> Enabled 180.0 °C
THS to Start LOL (Loss of Life) Calculation:	<input type="checkbox"/> Disabled 110.0 °C
LOL (Loss Of Life) Trip Setting:	2.0 days

Figure 13. TOEWS Settings.

This is a predictive system that also permits operators to respond proactively to possible thermal limit conditions, allowing them to mitigate system conditions in time. Similarly, the relay can also predict the loss of life of a transformer into the future time intervals mentioned before. The setting engineer can implement the amount of loss of life that he/she is willing to sacrifice. A rating methodology was discussed previously that can help in establishing the winding hottest-spot temperature and loss of life limits. **Figure 14** shows an example of how the TOEWS works.

As shown, the thermal settings show a maximum winding hottest-spot temperature of 150 °C. At this temperature, the relay issues a thermal trip. The loss of life trip is set to 3 days. This is the maximum number of days that the transformer is allowed to lose life before a trip is issued. Figure 14's top graph shows the loading characteristics of a given transformer. Its initial load was set to 70% of its nameplate rating for 1 hour. The load was then raised to 100% for one more hour. Ultimately, the load was increased to 130% of the nameplate rating and kept constant for two hours. The second graph shows the behavior of the winding hottest-spot temperature curve with the changing load. It can be seen that 2 hours after the load was increased to 130%, the winding hottest-spot temperature reached its tripping settings at 150 °C. The loss of life curve also shows a trip since the winding hottest-spot temperature has caused the loss of life to reach 3 days. The last graph in Figure 14 shows the early warning system method that lets operators know in advance of the future winding hottest-spot temperature values. As can be observed, the algorithm issued a 30 and 15 min warning before the hottest-spot temperature reached the 150 °C level. As indicated, the TOEWS also issued a tripping signal.

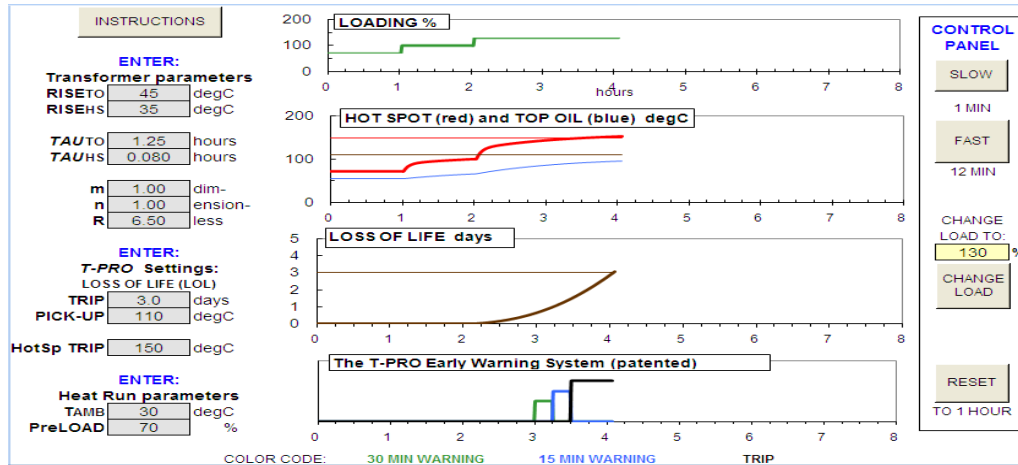


Figure 14. TOEWS Stages.

Conclusion

As determined in this paper, understanding the fundamental principles of thermal loading for power transformers is a critical factor in comprehending overload limitations for power transformers. The limitation on the loss of life of the insulation and the winding hottest-spot temperature are the driving factors for overload limits. These limitations allow us to create dynamic ratings and philosophies that give us guidelines for loading transformers beyond nameplate ratings. A microprocessor relay capable of protecting transformers for thermal overloads based on thermal principles of the IEEE C57.91-1995 guide was presented. In addition, an early warning system method was introduced that alerts system operators in advance of possible temperature violations.

This paper should provide relay engineers with the basic principles of thermal loading and protection. The microprocessor relay simplifies calculations and enables easier implementation. Nevertheless, a clear understanding of the thermal limitations of power transformers is necessary to apply the thermal settings. The engineer is encouraged to become very familiar with the IEEE C57.91-1995 standard if he or she wishes to know more about the loading of power transformers.

References

- [1] ABB Management Services Ltd. 2006. *Service Handbook for Transformers*. ABB Ltd., Zurich, Switzerland.
- [2] Aicher, L. C. 1976. Loading power transformers beyond nameplate rating. Pages 59-64 in W. J. McNutt, ed., *Application of Distribution and Power Transformers*. The Institute of Electrical and Electronics Engineers Inc., New York, New York, USA.
- [3] ERLPhase Power Technologies. 2008. *T-PRO Transformer Protection Relay User Manual Version 3.3 Rev 1*. Author, Winnipeg, Manitoba, Canada.
- [4] Gebert, K. and E. Edwards. 1974. *Transformers*. 12th ed. American Technical Publishers, Homewood, Illinois.
- [5] Heathcote, M. J. 1998. *The J&P Transformer Book*. Newnes, Boston, Massachusetts, USA.
- [6] Hunt, R. and M. L. Giordano. 2005. Thermal overload protection of power transformers operating theory and practical experience. 59th Annual Protective Relaying Conference. Georgia Tech, Atlanta, Georgia.
- [7] Iliff, L. C. 1976. Insulation coordination and dielectric tests. Pages 19-26 in W. J. McNutt, ed., *Application of Distribution and Power Transformers*. The Institute of Electrical and Electronics Engineers Inc., New York, New York, USA.
- [8] Institute of Electrical and Electronic Engineers. 1995. IEEE Guide for Loading Mineral-Oil Immersed Power Transformers. IEEE Standard C57.91. Author, New York, New York, USA.

- [9] Institute of Electrical and Electronic Engineers. 2000. IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers. IEEE Std C57.12.00. Author, New York, New York, USA.
- [10] Kulkarni, S. V. and S. A. Khaparde. 2004. *Transformer Engineering Design and Practice*. Marcel Dekker, New York, New York, USA.
- [11] Lockie, A. M. 1976. Loading distribution transformers beyond nameplate rating, Pages 50-58 in W. J. McNutt, ed., *Application of Distribution and Power Transformers*. The Institute of Electrical and Electronics Engineers Inc., New York, New York, USA.
- [12] Montsinger, V. M. and Ketchum. 1942. Emergency overloading of air-cooled oil-immersed power transformers by hot-spot temperatures. *Transactions of the American Institute of Electrical Engineers* 61(12):906–916.

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Biography

Joe Perez is a Sales Application Engineer for the relay and digital fault recorder products of ERLPhase Power Technologies, formerly NXPPhase T&D. He previously worked as a transmission engineer and a field application engineer, gaining experience in system protection projects and transmission system studies, including fault, power flow, and contingency analysis. Joe graduated from Texas A&M University in 2003 with a BSEE and resides in the Bryan/College Station, Texas area. He is an active member of IEEE and the Power System Relaying Committee.