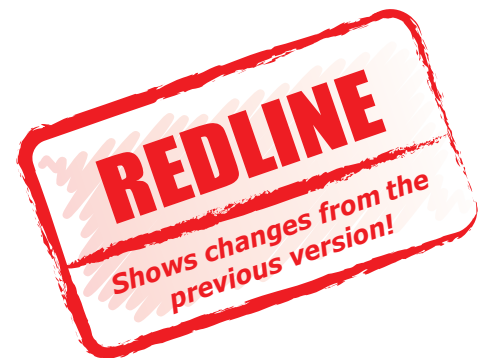


IEEE Guide for Loading Dry-Type Distribution and Power Transformers

IEEE Power and Energy Society

Sponsored by the
Transformers Committee



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IEEE Guide for Loading Dry-Type Distribution and Power Transformers

Sponsor

Transformers Committee
of the
IEEE Power and Energy Society

Approved 11 December 2013

IEEE-SA Standards Board

Abstract: General recommendations for the loading of dry-type distribution and power transformers installed in ventilated, non-ventilated, and sealed type enclosures are included in this standard.

Keywords: ambient temperature, constant load, hottest-spot temperature, IEEE C57.96™, loading capability, loading transformer, rated output, resin-encapsulated, solid-cast transformer, time constant, transient loading

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Introduction

This introduction is not part of IEEE Std C57.96-2013, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.

This guide covers the loading of dry-type distribution and power transformers and has been developed to cover modern dry-type transformers through 10 000 kVA. The insulation systems referred to in this document meet the thermal evaluation criteria established by the now withdrawn IEEE Std C57.12.56™-1986^a or the replacement document, IEEE Std C57.12.60™.

Work completed by the IEEE Insulation Life Subcommittee, comprising life test on transformer models, is the basis for the insulation life versus temperature relationship, designated as minimum life expectancy in IEEE Std C57.12.56-1986 and IEEE C57.12.60, which in turn are based on the Arrhenius reaction rate theory. To avoid ambiguity, this guide will use the term “life expectancy” to indicate the life to be expected at a given temperature. The “normal life expectancy” at rated hottest-spot temperature in a 30 °C ambient is expected to be 20 years. For calculation purposes, 180 000 h is used as the expected lifetime.

This revision of the guide combined the content for all dry-type transformers, including those with solid-cast and/or resin-encapsulated epoxy windings into the main body of the document. In addition, the computer programs in Annex B have been updated to include all transformer types, and detailed examples of loading and aging have been provided in Annex C. Moreover, the document has been updated to reflect the current IEEE Style Guide format.

^a Information on references can be found in Clause 2.

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IEEE Guide for Loading Dry-Type Distribution and Power Transformers

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1. Overview

1.1 Scope

This guide covers general recommendations for the loading of dry-type distribution and power transformers ~~that have 80 °C, 115 °C, and 150 °C average winding rises and insulation systems limited to 150 °C, 180 °C, and 220 °C maximum hottest spot operating temperatures, respectively. The guide includes recommendations for~~ installed in ventilated, non-ventilated, and sealed ~~dry-type transformers having impregnated insulation systems. For more specific recommendations for a particular transformer, the manufacturer of that transformer should be consulted~~ type enclosures.

1.2 Purpose

This document provides users with guidelines and limitations for loading dry-type transformers according to nameplate rating. Guidance is also provided for assessing the risks and consequences of loading above nameplate rating.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.~~

IEEE Std C57.12.01-1998 TM IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid-Cast and/or Resin Encapsulated Windings.^{1,2}

IEEE Std C57.12.56 TM 1986 (~~Reaff 1998~~), IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers.

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² IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, ~~P.O. Box 1331~~ Piscataway, NJ ~~08855-1331~~ 08854, USA (<http://standards.ieee.org/>).

[IEEE Std C57.12.60™, IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Dry-Type Power and Distribution Transformers, Including Open-Wound, Solid-Cast, and Resin-Encapsulated Transformers.](#)

[IEEE Std C57.94™, IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers.](#)

[IEEE Std C57.110™, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.](#)

[IEEE Std C57.134™, IEEE Guide for Determination of Hottest-Spot Temperature in Dry-Type Transformers.](#)

~~IEEE Std C57.12.59 1989, IEEE Guide for Dry Type Transformer Through Fault Current Duration (withdrawn).⁴~~

~~IEEE Std C57.94 1982 (Reaff 1987), IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry Type General Purpose Distribution and Power Transformers.~~

~~IEEE Std C57.110 1998, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.~~

⁴~~IEEE Std C57.12.59 1989 has been withdrawn; however copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).~~

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.³

dry-type transformer: A transformer in which the core and coils are in a gaseous or dry compound insulating medium.

non-ventilated dry-type transformer: A dry-type transformer that is so constructed as to provide no intentional circulation of external air through the transformer and operating at zero gauge pressure.

sealed transformer: A dry-type transformer with a hermetically sealed tank.

ventilated dry-type transformer: A dry-type transformer that is so constructed that the ambient air may circulate through its enclosure to cool the transformer core and windings.

4. Overview

4.1 General information

~~It must be recognized that~~ The recommendations given in this guide are based solely on the thermal characteristics of dry-type transformers. The insulation systems referred to in this document meet the thermal evaluation criteria established by the now withdrawn IEEE Std C57.12.56-1986⁴ or the replacement document, IEEE Std C57.12.60.

³ IEEE Standards Dictionary Online subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

⁴ Information on references can be found in Clause 2.

Loads above rating, based on this guide, may be applied only after a thorough study has been made of all the other various limitations that may be involved. Among these limitations are gas expansion and pressure in sealed dry-type units ~~and, in both ventilated and sealed transformers;~~² the thermal capability of associated equipment, such as bushings, leads, connections, tap changers in all dry-type transformers; and ancillary equipment, such as cables, reactors, circuit breakers, disconnecting switches, and current transformers. Also, limitations may be imposed by voltage regulation necessary for satisfactory operation of connected apparatus and by the increased operating costs due to the higher losses accompanying loads above nameplate rating. These may constitute the practical limit on load-carrying ability and should be considered before applying loads in excess of nameplate rating.

It is intended that dry-type transformers be installed based on the recommendations given in IEEE Std C57.94-~~1982~~.¹ If dry-type transformers are installed in subsurface vaults or ~~enclosures~~ areas of minimum size where the natural ventilation ~~is insufficient to prevent marked changes in the~~ will significantly raise ambient temperature with changes in transformer losses, ~~then~~ the increase in effective ambient temperature for expected increased transformer losses must be determined before loading limitations can be estimated.

Dry-type transformers are generally designed to permit loading in line with these guides, but if there are any questions as to the capability of a particular transformer to carry the desired load, the manufacturer should be ~~asked~~ consulted for specific recommendations.

4.2 Transformer life expectancy

Recommendations in this guide are based on the life expectancy of transformer insulation as affected by operating temperature and time and do not consider other factors that may affect transformer life, such as voltage stress or mechanical stress especially due to system voltage fluctuations or system faults.

¹ ~~Information on references can be found in Clause 2~~

The loading capability of transformers is related to properties of the insulating materials and insulation systems. Transformer life expectancy ~~at various operating temperatures~~ is not accurately known for many reasons, but primarily due to varying loads and operating temperatures over the life of a typical unit. However, the information given regarding loss of life of ~~the~~ insulation is better understood, is considered to be conservative, and is the best that can be produced from present knowledge of the subject. (~~The effects of temperature on insulation life are being investigated continuously, and new findings may affect future revisions of the guide.~~ The word “conservative” is used in the sense that the expected loss of insulation life for recommended load will not be greater than the amount stated.)

4.3 Transformer rated output

The rated kilovolt-ampere output of a transformer is ~~that the~~ load that it can deliver continuously at rated secondary voltage and rated frequency without exceeding the specified temperature rise under usual service conditions, as described in ~~Clause 4 of~~ IEEE Std C57.12.01-1998. The term “rated output” or “rated load” used in this guide refers to nameplate rating of continuously rated transformers. For transformers that do not have a continuous rating, ~~the manufacturer should be consulted for additional information~~ or when such information is not indicated on the nameplate or the transformer operating manual, the manufacturer should be consulted for additional information.

The temperature rise on which the rating is based takes into consideration ~~the~~ industry experience ~~of the industry~~ regarding the ~~following~~; insulation life as affected by operating temperature and the ambient temperature assumed to exist throughout the life of the transformer. The actual output that a transformer can deliver at any time in service, without undue deterioration of the insulation, may be more or less than the rated output, depending upon insulation temperature rating, the ambient temperature, altitude, and other attendant operating conditions.

4.4 Aging of insulation

Aging or deterioration of insulation is a function of time and temperature. Since, in most apparatus, the temperature is not uniform, the part that is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, aging studies consider the aging effects produced by the highest temperature. [In the transformer winding, this is known as the hottest-spot temperature. Additional information on how to determine the hottest-spot temperature for dry-type transformers may be found in IEEE Std C57.134.](#)

Practically all of the data in reference to the aging of insulation at different temperatures has been obtained in laboratory tests in which the changes in mechanical or electrical properties, or both, have been measured.

The relation between the life expectancy of insulation, as indicated by laboratory tests, and the actual life of a transformer is largely theoretical. Thus, loading based on such information should be tempered by sound judgment based on experience.

Because the cumulative effects of temperature and time in causing deterioration of transformer insulation are not thoroughly established, it is not possible to predict with a great degree of accuracy the length of life of a transformer, even under constant or closely controlled conditions, much less under widely varying service conditions. [However, the cumulative effects of repeated or long-time higher-than-normal operating temperatures can lead to deterioration of the mechanical and dielectric properties of the insulation. If this deterioration proceeds far enough, it may significantly reduce the life of the transformer, particularly if the apparatus is subjected to system short-circuits or over-voltage stresses.](#)

The change in rate of deterioration with change in temperature has been widely studied, but the amount of change in actual transformer life with a change in operating temperature remains debatable. However, there is agreement that, in all of the methods of calculating the effect of operating temperature on insulation life, higher than normal operating temperatures, whether they are due to loads above rating or to high ambient [temperatures](#), result in some reduction in transformer life ~~expectancy~~.

The many variables mentioned, and particularly the many varying conditions of load and ambient to which a transformer can be subjected in service, make it impossible to give precise rules for the loading of transformers. However, it is possible to give suggested loading under specified conditions to assist the user in making [informed](#) loading decisions.

4.5 Ambient temperature

Ambient temperature is an important factor in determining the load capability of a transformer, since the temperature rise for any load must be added to the ambient to determine the operating temperature. Whenever the actual ambient temperature can be determined from readings taken at the time of the load [pattern](#) being considered, such temperatures should be used to determine the winding hottest-spot temperature and the load capability of the transformer. It is often necessary to predict the load that a transformer can carry with no sacrifice of life expectancy at some future time when the actual ambient temperature is unknown. For dry-type transformers used in indoor installations, the ambient temperature can be approximated from heating or air conditioning records of the installation. For transformers used outdoors, the ambient temperature for the month in which the expected load is anticipated can be obtained from reports gathered by the Climatic Services Branch of the National Climatic Data Center, which is a part of the National Oceanic and Atmospheric Administration [\[B6\]](#). These reports are available for areas throughout the world.²

These ambient [temperatures](#) should be used as follows:

- For loads with normal life expectancy, use the average temperature over a period of years for the month involved.
- For short-time loads above rating with moderate sacrifice of life expectancy, use the average of the daily maximum temperatures for the month involved averaged with similar values for the same month over a period of years.

²This information can be obtained by writing to the National Climatic Data Center, Federal Bldg., Asheville, NC 28801.

5. Loading equations

5.1 Continuous loading

The hottest-spot winding temperature ~~rise as a function of load for steady-state conditions may be calculated by the following~~ may be calculated by Equation (1):

$$\theta_{HS} = \theta_a + \Delta \theta_{HS} \quad (1)$$

where,

θ_{HS} is the hottest-spot winding temperature, ~~at load L~~ , in °C

θ_a is the ambient temperature, in °C

$\Delta \theta_{HS}$ is the hottest-spot temperature rise over ambient ~~at per unit load L~~ , in °C,

The hottest-spot temperature rise as a function of load for steady-state conditions and self-cooled operation ~~may be calculated by Equation (2) through Equation (4):~~

$$\Delta \theta_{HS} = \Delta \theta_{HS,r} \times [L]^{2m} \quad (2)$$

where,

$\Delta \theta_{HS}$ is the hottest-spot temperature rise over ambient, in °C

$\Delta \theta_{HS,r}$ is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C ~~[tested values for self-cooled operation for use in Equation (A.2) may be different than tested values for fan-cooled operation for use in Equation (A.3)]~~

L is the per unit load

m is an empirical constant ~~which is equal to~~ (0.8 is suggested unless [another value can be justified by](#) test data [is available](#))

Fan-cooled operation [is calculated as follows:](#)

$$\Delta \Theta_{HS} = \Delta \Theta_{HS,r} \times [L^2 K_T]^X \quad (3)$$

[where,](#)

[\$\Delta \Theta_{HS}\$](#) is the hottest-spot temperature rise over ambient, in °C

[\$\Delta \Theta_{HS,r}\$](#) is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

[\$L\$](#) is the per unit load

K_T is the temperature correction for resistance change with temperature

X is an empirical constant used in forced-air calculation (1.0 is suggested unless [another value can be justified by](#) test data ~~is available~~)

$$K_T = \frac{T_k + \Delta \Theta_{HS}}{T_k + \Delta \Theta_{HS,r}} \quad (4)$$

[where,](#)

[\$K_T\$](#) is the temperature correction for resistance change with temperature

$\Delta\theta_{HS}$ is the hottest-spot temperature rise over ambient, in °C

$\Delta\theta_{HS,r}$ is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

T_k is the temperature constant for conductor ~~which is~~ (225 for aluminum and 234.5 for copper)

Test data indicates that ~~the above~~ Equation (2) through Equation (4), although only approximate, should result in conservative predictions of the hottest-spot temperature. The m exponent of 0.8 for self-cooled operation and the X exponent of 1.0 for forced-air operation are derived from heat transfer correlations for natural and forced convection. Test data indicates that a temperature correction for resistance given by Equation (4) is required to predict hottest-spot temperatures during forced-air loading due to the higher losses present at forced-cooled operation.

Equation (2) and Equation (3) ignore eddy losses in the winding, which vary inversely with temperature. Eddy losses are usually less than 10% of the load losses unless harmonic currents are present. Equation (3) requires an iterative calculation procedure. Using the suggested exponents and considering the resistance change with temperature for fan-cooled operation should result in conservative calculations of the hottest spot temperature rise, even when eddy losses are ignored. If harmonic currents are present, the increased eddy losses during overloading may need consideration in accordance with IEEE Std C57.110-1998.

5.2 Transient loading

The hottest-spot temperature due to transient overloading may be determined ~~by the following~~ by Equation (5) and Equation (6):

$$\Delta\theta_t = (\Delta\theta_U - \Delta\theta_i) \times \left[1 - \exp\left(-\frac{t}{\tau_r}\right) \right] + \Delta\theta_i \quad (5)$$

$$\Delta\theta_t = (\Delta\theta_U - \Delta\theta_i) \left[1 - \exp\left(-\frac{t}{\tau}\right) \right] + \Delta\theta_i \quad (A.5)$$

where,

$\Delta\theta_t$ is the hottest-spot temperature rise at some time t after the overload, in °C

$\Delta\theta_i$ is the initial hottest-spot rise at some prior load L_i , in °C

$\Delta\theta_U$ is the ultimate hottest-spot rise if the per unit overload L_u , continued until the hottest-spot temperature stabilized, in °C

t is the time, in minutes

τ_r is the time constant in minutes for the transformer at rated load

$$\theta_{HS} = \Delta\theta_t + \theta_a \quad (6)$$

where,

θ_{HS} is the hottest-spot temperature, in °C

$\Delta\theta_t$ is the hottest-spot temperature rise at some time t after the overload, in °C

θ_a is the ambient temperature, in °C

5.3 Time constants

The concept of a transformer time constant is based on the assumption that a single heat source supplies heat to a single heat sink and that the temperature rise of the sink is an exponential function of the heat input. The time constant is ~~defined as~~ the time required for the temperature of the winding to reach 63.2% of a stabilized temperature at any load. In this context, the time constant is the time required for the temperature rise over ambient to change 63.2% after a step change in load. For loading purposes, it is desirable to have as large a time constant as possible. Hottest-spot temperature calculations for loading should be made on both the low-voltage and high-voltage windings, since published test data indicates that the time constants may be different. Insulation system temperature classes for the two windings may also be different.

The time constant of a winding at rated load τ_r may be estimated by the Equation (7):

$$\tau_r = \frac{C(\Delta\theta_{HS,r} - \theta_e)}{P_r} \quad (7)$$

where

τ_r is the time constant in minutes for the transformer at rated load

C is the effective thermal capacity of winding, in watt-minutes per $^{\circ}\text{C}$ K
(Wmin/K),

$[15.0 \times \text{mass of aluminum conductor in kilograms (kg)}] + [6.35 \text{ } 24.5 \times \text{weight}$
mass of epoxy and/or other winding insulation in kilograms (kg)], or

$[6.42 \times \text{mass of copper conductor in kilograms (kg)}] + [24.5 \times \text{weight}$ mass of
epoxy and/or other winding insulation in kilograms (kg)]

~~=11.2 × weight of aluminum windings in kilograms, or~~

~~=6.39 × weight of copper windings in kilograms;~~

P_r is the I²R loss of a winding at rated load and rated temperature rise, in watts

$\Delta\theta_{HS,r}$ is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

θ_e is the core contribution to winding hottest-spot temperature rise at rated load, in °C

(5 °C for outer winding, other values may be used if test data is available)

~~=0 for outer (primary) winding,~~

~~(20~~ 25 °C for inner ~~(secondary)~~ winding, other values may be used if test data is available)

The time constant for any load and for any starting temperature for either a heating cycle or a cooling cycle may be estimated by Equation (8).

~~If m is equal to 1, Equation (A.7) is correct for any load and any starting temperature. If m is not equal to 1, the time constant for any load and for any starting temperature for either a heating cycle or a cooling cycle is given by Equation (A.8):~~

$$\tau = \tau_r \times \frac{\left(\frac{\Delta\theta_U}{\Delta\theta_{HS,r}}\right) - \left(\frac{\Delta\theta_i}{\Delta\theta_{HS,r}}\right)}{\left(\frac{\Delta\theta_U}{\Delta\theta_{HS,r}}\right)^{\frac{1}{m}} - \left(\frac{\Delta\theta_i}{\Delta\theta_{HS,r}}\right)^{\frac{1}{m}}} \quad (8)$$

$$\tau = \tau_{HS,r} \frac{\left(\frac{\Delta\theta_U}{\Delta\theta_{HS,r}}\right) - \left(\frac{\Delta\theta_i}{\Delta\theta_{HS,r}}\right)}{\left(\frac{\Delta\theta_U}{\Delta\theta_{HS,r}}\right)^{\frac{1}{m}} - \left(\frac{\Delta\theta_i}{\Delta\theta_{HS,r}}\right)^{\frac{1}{m}}} \quad (\text{A.8})$$

where,

τ is the time constant in minutes for the transformer at any load

τ_r is the time constant in minutes for the transformer at rated load

$\Delta\theta_U$ is the ultimate hottest-spot rise if the per unit overload LU, continued until the hottest-spot temperature stabilized, in °C

$\Delta\theta_i$ is the initial hottest-spot rise at some prior load Li, in °C

$\Delta\theta_{HS,r}$ is the rated or tested hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

m is an empirical constant, which is equal to 0.8 (suggested unless test data is available)

Time constants may also be estimated from the hot resistance cooling curve obtained during thermal tests. The manufacturer may also be consulted for more accurate estimations of the winding time constants than estimated by ~~the above~~ Equation (7) and Equation (8). Consideration may be given to specifying that time constants be shown on test reports when supplied.

5.4 Calculation of loading capability

5.4.1 Loading in standard conditions

Equation (1) through [Equation \(8\)](#) may be used to determine hottest-spot temperatures during overloads. They may also be used to determine the short-time or continuous loading, ~~which results in the maximum temperatures given in Table A.1 or any other limiting temperatures.~~

The initial hottest-spot rise for prior load L_i may be obtained from Equation (2 ~~and~~). ~~It is determined as follows:~~[in Equation \(9\)](#):

$$\Delta\theta_i = \Delta\theta_{HS,r} \times [L_i]^{2m} \quad (9)$$

[where,](#)

[\$\Delta\theta_i\$](#) is the hottest-spot temperature rise at the prior per unit load, in °C

[\$\Delta\theta_{HS,r}\$](#) is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

[\$L_i\$](#) is the prior per unit load

[\$m\$](#) is an empirical constant, which is equal to 0.8 (suggested unless test data is available)

From Table 1, select the rated hottest-spot [winding](#) temperature T_{HS} . ~~For the ambient temperature, determine the permissible hottest-spot temperature rise at time t from Equation (A.1).~~

Table 1 — Constants for lifetime equation

Insulation system temperature °C	Rated hottest-spot winding temperature °C	Arrhenius' equation constants					
		6 °C		8 °C		10 °C	
		ln(a)	b	ln(a)	b	ln(a)	b
130	120	−34.011	18 129	−22.656	13 665	−15.844	10 986
150	140	−36.321	20 006	−24.389	15 076	−17.230	12 118
180	170	−39.787	22 994	−26.988	17 322	−19.309	13 919
200	190	−42.098	25 102	−28.721	18 907	−20.696	15 190
220	210	−44.408	27 302	−30.454	20 560	−22.082	16 515

(New)

For the ambient temperature, determine the permissible hottest-spot temperature rise at time t from Equation (1), as shown in Equation (10).

$$\Delta\theta_t = \theta_{HS} - \theta_a \quad (10)$$

where,

$\Delta\theta_t$ is the hottest-spot temperature rise at time t, in °C

θ_{HS} is the hottest-spot winding temperature, in °C

θ_a is the ambient temperature, in °C

Determine the ultimate hottest-spot temperature rise from Equation (5), as shown in Equation (11).

$$\Delta\theta_U = \left[\frac{\Delta\theta_t - \Delta\theta_i}{1 - \exp\left(-\frac{t}{\tau}\right)} \right] + \Delta\theta_i \quad (11)$$

where,

$\Delta\theta_U$ is the ultimate hottest-spot rise if the per unit overload L_u , continued until the hottest-spot temperature stabilized, in °C

$\Delta\Theta_t$ is the hottest-spot temperature rise at some time t after the overload, in °C

$\Delta\Theta_i$ is the initial hottest-spot rise at some prior load L_i , in °C

t is the duration of the overload, in minutes

τ is the time constant in minutes for the transformer

From Equation (2), the overload corresponding to these conditions may be obtained as in Equation (12):

~~The time constant t may be obtained from manufacturer's data or estimated. Select a time t for the duration of the overload to substitute in the above equation. From Equation (A.2) the overload corresponding to these conditions may be obtained as follows:~~

$$L_U = \left[\frac{\Delta\Theta_U}{\Delta\Theta_{HS,r}} \right]^{\frac{1}{2m}} \quad (12)$$

where,

L_U is the overload in per unit load

$\Delta\Theta_U$ is the ultimate hottest-spot rise if the per unit overload L_U , continued until the hottest-spot temperature stabilized, in °C

$\Delta\Theta_{HS,r}$ is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

m is an empirical constant, which is equal to 0.8 (suggested unless test data is available)

A similar derivation based on Equation (3) results in the Equation (13) for forced air operation:

$$L_U = \sqrt{\frac{\left[\frac{\Delta\Theta_U}{\Delta\Theta_{HS,r}}\right]^{\frac{1}{X}}}{K_T}} \quad (13)$$

where,

L_U is the overload in per unit load

$\Delta\Theta_U$ is the ultimate hottest-spot rise if the per unit overload L_U , continued until the hottest-spot temperature stabilized, in °C

$\Delta\Theta_{HS,r}$ is the rated hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

X is an empirical constant used in forced-air calculation, which is 1.0 (suggested unless test data available)

K_T is the temperature correction for resistance change with temperature

~~A PC BASIC program to perform the calculations is given in A.8.7.~~

5.4.2 Influence of ambient temperature.

The average ambient temperature should cover periods ~~of time~~ not exceeding 24 h, with the maximum temperature not more than 10 °C greater than the average temperature. For each degree Celsius that the average temperature of the cooling air is above or below 30 °C, a transformer may be loaded below or above its nameplate kilovolt-ampere rating for any period ~~of time~~, as specified in Table 2. Loading based on ~~the basis of~~ ambient temperature with the loads permitted by Table 2 can give approximately the same life expectancy as if the transformers had been operated at nameplate rating and standard ambient temperatures over the same period. The operation of transformers in cooling air above 50 °C_r or below 0 °C_r is not covered by Table 2, and the manufacturer should be consulted for these operating conditions. Since the ambient temperature is an important factor in determining the load capability of a transformer, it should be controlled for indoor installations by adequate ventilation, and it should always be considered in outdoor installations.

Table 2 – Continuous per unit loading capability as a function of ambient temperature

Cooling mode	24 h average ambient temperature °C	Insulation temperature class				
		130	150	180	200	220
AA, <u>ANV</u>	<u>0</u>	<u>1.20</u>	<u>1.16</u>	<u>1.13</u>	<u>1.11</u>	<u>1.10</u>
	10	~~1.20~~ <u>1.13</u>	~~1.16~~ <u>1.11</u>	~~1.12~~ <u>1.09</u>	<u>1.08</u>	<u>1.07</u>
	20	~~1.13~~ <u>1.07</u>	~~1.11~~ <u>1.06</u>	~~1.08~~ <u>1.04</u>	<u>1.04</u>	<u>1.03</u>
	30	~~1.07~~ <u>1.00</u>	~~1.06~~ <u>1.00</u>	~~1.04~~ <u>1.00</u>	<u>1.00</u>	<u>1.00</u>
	40	~~1.00~~ <u>0.93</u>	~~1.00~~ <u>0.94</u>	~~1.00~~ <u>0.95</u>	<u>0.96</u>	<u>0.96</u>
	<u>50</u>	<u>0.85</u>	<u>0.88</u>	<u>0.91</u>	<u>0.92</u>	<u>0.93</u>
<u>AA/FA</u> , <u>AFA</u>	<u>0</u>	<u>1.15</u>	<u>1.13</u>	<u>1.10</u>	<u>1.09</u>	<u>1.08</u>
	10	~~1.15~~ <u>1.11</u>	~~1.13~~ <u>1.09</u>	~~1.10~~ <u>1.07</u>	<u>1.06</u>	<u>1.05</u>
	20	~~1.11~~ <u>1.05</u>	~~1.09~~ <u>1.04</u>	~~1.07~~ <u>1.04</u>	<u>1.03</u>	<u>1.03</u>

Cooling mode	24 h average ambient temperature °C	Insulation temperature class				
		130	150	180	200	220
	30	~~1.05~~ 1.00	~~1.04~~ 1.00	~~1.03~~ 1.00	1.00	1.00
	40	~~1.00~~ 0.94	~~1.00~~ 0.95	~~1.00~~ 0.96	0.97	0.97
	50	0.88	0.9	0.93	0.94	0.94
NOTE—Cooling mode designations may be found in IEEE Std C57.12.01						

Table 2 per unit AA and ANV loading capability values are calculated from Equation (15) which is derived from Equation (1) and Equation (2) as in Equation (14):

$$\Theta_{HS} = \Theta_a + \Delta \Theta_{HS,r} \times [L]^{2m} \quad (14)$$

Solving for the per unit load L , the equation then becomes:

$$L = \left[\frac{\Theta_{HS} - \Theta_a}{\Delta \Theta_{HS,r}} \right]^{0.625} \quad (15)$$

where,

Θ_{HS} is the hottest-spot winding temperature, in °C, as defined in Table 1

Θ_a is the ambient temperature, in °C, equal to the 24-h average ambient temperature in this case

$\Delta \Theta_{HS,r}$ is the rated or tested hottest-spot temperature rise over ambient at 1.0 per unit load, in °C

L is the per unit load

m is an empirical constant, which is equal to 0.8 (suggested unless test data is available)

[Table 2 per unit AA/FA and AFA loading capability values are calculated in a similar fashion from Equation \(1\) and Equation \(3\). Note, however, that the resistance temperature correction factor \$K_T\$ was not used to develop the table values, since these factors are intended to be estimates, and it would not be possible to properly vary the correction factor for the different temperature classes in a single table. More accurate load factors may be calculated for specific application conditions by using the reference equations with the proper resistance temperature correction factor.](#)

5.4.3 Influence of altitude on loading

Because [dry-type](#) transformers are dependent ~~up~~ on air for dissipation of heat loss, the effect of ~~the~~ decreased air density due to high altitude is to increase the temperature rise of the transformers. Transformers may be operated at rated kilovolt-amperes at altitudes greater than 1000 m ~~(3300 ft)~~ without exceeding temperature limits, provided the average temperature of the cooling air does not exceed the values of [Table 23](#) for the respective altitudes. [The cooling air temperatures are based on an increase in average winding temperature rise of 0.5% for every 100 m above 1000 m altitude for natural cooling and 1.0% for forced-air cooling.](#) The data included in [Table 23](#) apply to ventilated dry-type [and non-ventilated dry-type](#) transformers only, ~~and~~ and are not applicable to sealed ~~and nonventilated dry-type~~ or gas-filled transformers. [An altitude of 4500 m is considered a maximum for dry-type transformers conforming to IEEE Std C57.12.01](#)

**Table 3 — Maximum allowable 24-h average temperature of cooling air
in °C for operation at rated kilovolt-amperes with normal loss of life
under unusual altitude conditions**

Insulation temperature class AA, ANV cooling	Rated average winding temperature rise °C	Altitude			
		1000 m	2000 m	3000 m	4000 m
130	75	30	26	23	19
150	90	30	26	21	17
180	115	30	24	19	13
200	130	30	24	17	11
220	150	30	23	15	8
Insulation temperature class AA/FA, AFA cooling	Rated average winding temperature rise °C	Altitude			
		1000 m	2000 m	3000 m	4000 m
130	75	30	23	15	8
150	90	30	21	12	3
180	115	30	19	7	-5
200	130	30	17	4	-9
220	150	30	15	0	-15

(New)

NOTE—Cooling mode designations may be found in IEEE Std C57.12.01

**~~Table 1—Self-cooled continuous loading on basis of average ambient
temperature~~**

Type of unit	Maximum rated hottest-spot temperature (°C)	Hottest-spot temperature in a 30 °C ambient (°C)	Percent of rated kVA/°C increase for average ambient less than 30 °C, or decrease for average ambient greater than 30 °C
Ventilated self-cooled	150	140	(0.57)
	180	170	(0.43)
	220	210	(0.35)
Sealed self-cooled	150	140	(0.65)
	180	170	(0.49)
	220	210	(0.40)

(Deleted)