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IEEE Std C57.96-1989)

IEEE Guide for Loading Dry-Type Distribution and Power Transformers

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

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Abstract: 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, are covered in this guide. Recommendations for ventilated, nonventilated, and sealed dry-type transformers having impregnated insulation systems are included.

Keywords: ambient temperature, cast-resin transformer, constant load, derating factors, hottest-spot temperature, loading capability, loading transformer, rated output, resin-encapsulated, solid-cast, time constant, transient loading

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Introduction

(This introduction is not part of IEEE Std C57.96-1999, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.)

This guide covers loading dry-type distribution and power transformers with 80 °C, 115 °C, and 150 °C average winding rises, and has been developed to cover modern dry-type transformers through 10 000 kVA.

The 150 °C, 180 °C, and 220 °C insulation systems meet the thermal evaluation criteria established by IEEE Std C57.12.56-1986.[a]

Work completed by the IEEE Insulation Subcommittee, comprising life test on transformer models, is the basis for the insulation life vs. temperature relationship, designated as minimum life expectancy in IEEE Std C57.12.56-1986, which in turn is based on the Arrhenius reaction rate theory. To avoid ambiguity, this guide will use the term *normal life expectancy* to indicate the life to be expected at a given temperature. The normal life expectancy at 140 °C, 175 °C, and 210 °C hottest-spot temperature in a 30 °C ambient for 80 °C, 115 °C, and 150 °C rise transformers, respectively, is 20 y.

The load profile used in the preparation of the loading tables in this guide was chosen as a representative daily cycle. Loss of life was determined by computer computation of the actual hottest-spot profile for the load cycle and ambient conditions. This method of calculation is more accurate than previous methods. Hand-calculation methods are illustrated in Clause 6.

The assumed characteristics were obtained by a consensus of users and manufacturers as being the best typical characteristics for modern transformers.

Annex A of this guide was developed for ventilated dry-type distribution and power transformers with solid-cast and/or resin-encapsulated epoxy windings manufactured in accordance with IEEE Std C57.12.01-1998. This annex contains complete information for loading cast-resin transformers. Reference to the main part of the guide is not required.

There are many cast-resin transformer designs available with different insulation temperature classes. Current practice by manufacturers has been to rely on tests of individual materials to determine the rated insulation temperature class to assign to their designs. Operating experience indicates that this gives acceptable life when cast-resin transformers are operated at nameplate ratings. At the present time industry has not established Arrhenius insulation aging curves to give loss of insulation life for cast-resin transformer windings operated above the rated insulation temperature class.

The loading recommendations and equations presented represent the best available information based on a consensus of users and manufacturers of cast-resin transformers at the time this guide was approved. Although this document is not a performance standard, it is expected that manufacturers will perform testing to substantiate their performance claims and demonstrate that the loading of their designs equals or exceeds these recommendations.

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[a] Information on references can be found in Clause 2 and A.2.

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IEEE Guide for Loading Dry-Type Distribution and Power Transformers

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 ventilated, nonventilated, 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.

1.2 General information

It must be recognized that the recommendations given in this guide are based solely on the thermal characteristics of dry-type transformers. 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, the thermal capability of associated equipment, such as bushings, leads, connections, tap changers; 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 of minimum size where the natural ventilation is insufficient to prevent marked changes in the 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 for specific recommendations.

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[1] Information on references can be found in Clause 2.

1.3 Transformer life expectancy

Recommendations in this guide are based on life expectancy of transformer insulation as affected by operating temperature and time.

Transformer life expectancy at various operating temperatures is not accurately known, but the information given regarding loss of life of insulation is considered to be conservative, and 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.)

1.4 Transformer rated output

The rated kilovolt-ampere output of a transformer is that 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 when such information is not indicated on the nameplate.

The temperature rise on which the rating is based takes into consideration the experience of the industry regarding the following:

a) Insulation life as affected by operating temperature; and
b) 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 the ambient temperature, altitude, and other attendant operating conditions.

1.5 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.

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.

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 ambients, 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 loadings under specified conditions to assist the user in making loading decisions.

1.6 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 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. These reports are available for areas throughout the world.[2]

These ambients should be used as follows:

a) For loads with normal life expectancy, use the average temperature over a period of years for the month involved.

b) 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.

1.7 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 1.

Loading on the basis of ambient temperature with the loads permitted by Table 1 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, or below 0 °C, is not covered by Table 1; 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.

1.8 Influence of altitude on loading

Because transformers are dependent upon 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.

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

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)

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 2 for the respective altitudes. The data included in Table 2 apply to ventilated dry-type transformers only, and are not applicable to sealed and nonventilated dry-type transformers.

Table 2—Maximum allowable 24 h average temperature of cooling air, in °C, for operation at rated kVA under unusual temperature and altitude conditions

Type of Apparatus	Altitude			
	1 000 m (3 300 ft)	2 000 m (6 600 ft)	3 000 m (9 900 ft)	4 000 m (13 200 ft)
Class AA				
80 °C rise	30	26	22	18
115 °C rise	30	24	18	12
150 °C rise	30	22	15	7
Class AA/FA and AFA				
80 °C rise	30	22	14	6
115 °C rise	30	18	7	–5
150 °C rise	30	15	0	–15

Transformers may be operated in a 30 °C ambient at altitudes greater than 1000 m (3300 ft) without exceeding temperature limits, provided the load to be carried is reduced below rating by the percentages given in Table 3 for each 100 m (330 ft) that the altitude is above 1000 m (3300 ft).

Table 3—Rated kVA derating factors for altitudes greater than 1000 m (3300 ft) at 30 °C average ambient temperature

Type of transformer	Types of cooling	Derating factor (%)[a]
Dry-type, self-cooled	AA	0.3
Dry-type, forced-air-cooled	AA/FA and AFA	0.5

[a] For each 100 m (330 ft).

2. References

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, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid-Cast and/or Resin-Encapsulated Windings.[3]

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

3. Basic loading conditions for normal life expectancy

3.1 Basic conditions

The basic loading conditions of a transformer for normal life expectancy are as follows:

a) The transformer is continuously loaded at rated kilovolt-amperes and rated delivered voltage.

b) The average temperature of the cooling air during any 24 h period is equal to 30 °C and the temperature of the cooling air at no time exceeds 40 °C.

c) The altitude does not exceed 1000 m (3300 ft).

The hottest-spot temperature of the winding is the sum of the ambient temperature, the average temperature rise, and the hottest-spot allowance. For dry-type transformers operating continuously under the foregoing conditions, the hottest-spot temperature has been assumed to be 140 °C for transformers incorporating Class 150 °C limiting temperature insulation system; 170 °C for transformers incorporating Class 180 °C limiting temperature insulation system; and 210 °C for transformers incorporating Class 220 °C limiting temperature insulation system in a 30 °C ambient. These hottest-spot temperatures are expected to yield a normal life expectancy of 20 y for transformers covered in this guide.

Unusual service conditions, as given in 4.2 of IEEE C57.12.01-1998, are not covered by this guide.

Years of experience have indicated that a transformer rated in accordance with IEEE C57.12.01-1998 and operated under the foregoing conditions will have an economically acceptable life.

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[3] IEEE publications are available from the Institute of Electrical and Electronic Engineers, 445 Hoes Lane, P.O. Box 1331 Piscataway NJ 08855-1331 USA (http://www.standards.ieee.org/).

[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/).

3.2 Loading for life expectancy under specified conditions

Transformers may be loaded above rated kilovolt-amperes with no sacrifice of life expectancy if the loads and the load correction factors are applied under the conditions specified in 3.3, 3.4, 3.5, and 3.6.

The loading values and corrections given here are compromise values for a wide variety of transformers, and they have been selected so that allowable loads for practically all transformers covered by this guide will be at least as great as those given.

3.3 Loading determined by measured temperature

Dry-type transformers may be loaded above rating for any period of time with normal life expectancy, provided that the 24 h average hottest-spot temperature of 210 °C for sealed units; and 140 °C, or 170 °C, or 210 °C for ventilated units, is not exceeded for transformers with 150 °C, 180 °C, and 220 °C insulation systems, respectively. Hottest-spot temperatures may be obtained from hottest-spot temperature indicators if they are available.

Because of the variations in the gradient between the winding conductor hottest-spot temperature and the top air or top gas temperature of various designs under full load, neither inside air temperature for ventilated or nonventilated dry-type transformers nor top gas temperature should be used alone as a guide in loading transformers. However, either may be used as a guide in loading if the variation of the winding conductor hottest-spot rise over inside air or gas temperature is known.

3.4 Loading on the basis of short-time loads

The permissible load on dry-type transformers may be increased above rated load for short times by the multipliers shown in Table 4, Table 5, and Table 6, provided that

a) The short-time peak load occurs not more than once in any 24 h period.

b) The short-time peak load does not exceed the values listed in Table 4, Table 5, and Table 6.

c) The short-time peak load follows, and is followed by, either a constant load or an equivalent constant load calculated by means of 6.1.

d) The limitations of 1.2 and the basic conditions of 3.1 are met.

The values given in Table 4, Table 5, and Table 6 were obtained from a computer program described in 6.3 and a time constant of 30 min was used for each of the insulation systems. The time constant of 30 min was chosen as a conservative value for all dry-type transformers. If data is available for a different time constant, similar tables can be generated using the computer program in 6.3. Care should be taken by users of the computer program to avoid load cycles that exceed the maximum temperatures given in Table 4, Table 5, and Table 6 without a thorough investigation for abnormal consequences.

3.5 Effects of various factors existing at one time

When two or more of the following factors affecting loading for normal life expectancy exist at one time, the effects are cumulative and the increase in loads due to each may be added to secure the maximum suggested load. (Each increase must be based on rated kilovolt-amperes.)

a) Loading on basis of ambient temperature;

b) Loading on basis of measured temperature rise;

c) Loading on basis of short-time loads above rating.

Table 4—Daily loads above rating to give normal life expectancy in 20 °C average ambient for transformers with a 30 min time constant

Peak load time in hours	**Times rated kVA**					
	150 °C insulation system following and followed by a constant load of					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.56	(210)	1.64	(217)	1.71	(220)
1	1.37	(196)	1.42	(203)	1.45	(206)
2	1.27	(181)	1.29	(185)	1.30	(186)
4	1.19	(165)	1.21	(169)	1.21	(169)
8	1.14	(155)	1.14	(156)	1.15	(158)
Peak load time in hours	**180 °C insulation system following and followed by a constant load of**					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.49	(255)	1.57	(261)	1.64	(266)
1	1.32	(239)	1.36	(245)	1.39	(249)
2	1.23	(221)	1.24	(224)	1.26	(229)
4	1.16	(204)	1.17	(206)	1.18	(209)
8	1.11	(191)	1.12	(194)	1.12	(194)
Peak load time in hours	**220 °C insulation system following and followed by a constant load of**					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.38	(282)	1.47	(290)	1.53	(292)
1	1.25	(269)	1.28	(274)	1.31	(278)
2	1.17	(251)	1.19	(254)	1.20	(259)
4	1.13	(238)	1.13	(239)	1.14	(241)
8	1.09	(227)	1.09	(227)	1.09	(227)

Table 5—Daily loads above rating to give normal life expectancy in 30 °C average ambient for transformers with a 30 min time constant

Peak load time in hours	Times rated kVA					
	150 °C insulation system following and followed by a constant load of					
	90%	Maximum hottest-spot temperature reached during load cycle (°C)	70%	Maximum hottest-spot temperature reached during load cycle (°C)	50%	Maximum hottest-spot temperature reached during load cycle (°C)
1/2	1.47	(204)	1.59	(216)	1.65	(220)
1	1.30	(192)	1.36	(201)	1.39	(206)
2	1.20	(177)	1.23	(183)	1.25	(186)
4	1.13	(164)	1.15	(168)	1.16	(169)
8	1.07	(153)	1.09	(156)	1.09	(156)
Peak load time in hours	180 °C insulation system following and followed by a constant load of					
	90%	Maximum hottest-spot temperature reached during load cycle (°C)	70%	Maximum hottest-spot temperature reached during load cycle (°C)	50%	Maximum hottest-spot temperature reached during load cycle (°C)
1/2	1.42	(249)	1.53	(261)	1.59	(267)
1	1.27	(236)	1.32	(244)	1.35	(248)
2	1.17	(216)	1.20	(223)	1.22	(228)
4	1.11	(201)	1.13	(206)	1.14	(209)
8	1.06	(189)	1.08	(194)	1.08	(194)
Peak load time in hours	220 °C insulation system following and followed by a constant load of					
	90%	Maximum hottest-spot temperature reached during load cycle (°C)	70%	Maximum hottest-spot temperature reached during load cycle (°C)	50%	Maximum hottest-spot temperature reached during load cycle (°C)
1/2	1.33	(278)	1.43	(289)	1.49	(291)
1	1.21	(267)	1.25	(274)	1.28	(278)
2	1.14	(251)	1.15	(254)	1.16	(257)
4	1.09	(237)	1.10	(240)	1.10	(240)
8	1.05	(225)	1.06	(228)	1.06	(228)

Table 6—Daily loads above rating to give normal life expectancy in 40 °C average ambient for transformers with a 30 min time constant

Peak load time in hours	**Times rated kVA**					
	150 °C insulation system following and followed by a constant load of					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.33	(192)	1.52	(214)	1.59	(217)
1	1.18	(179)	1.30	(199)	1.34	(204)
2	1.09	(166)	1.18	(183)	1.19	(184)
4	1.04	(157)	1.10	(168)	1.11	(170)
8	1.00	(150)	1.03	(155)	1.04	(157)
Peak load time in hours	**180 °C insulation system following and followed by a constant load of**					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.33	(240)	1.48	(260)	1.55	(264)
1	1.19	(226)	1.28	(244)	1.31	(248)
2	1.11	(201)	1.16	(223)	1.18	(228)
4	1.05	(197)	1.09	(206)	1.10	(209)
8	1.01	(187)	1.03	(192)	1.04	(194)
Peak load time in hours	**220 °C insulation system following and followed by a constant load of**					
	90%	**Maximum hottest-spot temperature reached during load cycle (°C)**	**70%**	**Maximum hottest-spot temperature reached during load cycle (°C)**	**50%**	**Maximum hottest-spot temperature reached during load cycle (°C)**
1/2	1.27	(273)	1.38	(285)	1.44	(290)
1	1.16	(262)	1.21	(262)	1.24	(276)
2	1.09	(246)	1.12	(255)	1.13	(257)
4	1.05	(235)	1.07	(241)	1.07	(241)
8	1.01	(222)	1.02	(226)	1.02	(226)

4. Loading transformers with moderate sacrifice of life expectancy

4.1 Factors affecting transformer life

Dry-type transformers may be loaded above rated kilovolt-amperes under conditions other than those specified in the preceding clauses, with a sacrifice of life expectancy dependent on the load capability of the transformer and on the actual operating conditions.

The overload capability of dry-type transformers varies widely and is affected by the following characteristics:

a) Hottest-spot winding conductor rise over ambient;

b) Ratio of load losses to no-load losses;

c) Time constant;

d) Ambient temperature.

Operating conditions for dry-type transformers are so variable that no single set of practical loading data can be presented for all possible combinations of conditions and loading. However, methods are outlined in this clause whereby the user can estimate allowable loads for the user's own conditions by taking into account the probable number and nature of such loads during the life of the transformer, and the approximate percentage of life expectancy that the user is willing to sacrifice.

In general, permissible temperatures and loads calculated by the means outlined here will be higher than those given in 3.2, which are necessarily conservative in order to cover the wide variation in sizes and makes of dry-type transformers.

The necessary curves, tables, equations, and definitions used as a basis for the methods given here are presented in Clause 6. Information given is considered to be the best that can be produced from the present knowledge of the subject. In spite of its approximate nature, it is believed that it will be of value as a guide to the user.

4.2 Aging of insulation due to operation above rated hottest-spot temperature

This guide assumes that the insulation deterioration relationship, with respect to temperature and time, follows an adaptation of the Arrhenius reaction rate theory, which states that the logarithm of insulation life is a function of the reciprocal of absolute temperature, as follows:

$$\log \text{life}\ (t) = (B_{10}/T) + A_{10} \tag{1}$$

or

$$\log_e \text{life}\ (t) = (B_e/T) + A_e$$

where

t is the time in hours,

T is the absolute temperature, in Kelvin, at the hottest spot (i.e., $\Theta_{HS} + 273$),

Θ_{HS} is the temperature, in degrees Celsius, at the hottest spot [see Equation (5)],

A_{10}, B_{10} are constants to the base 10 for the appropriate life expectancy curve of each insulation system as shown in Figure 1,

A_e, B_e are constants to the naperian base for the appropriate life expectancy curve of each insulation system as shown in Figure 2.

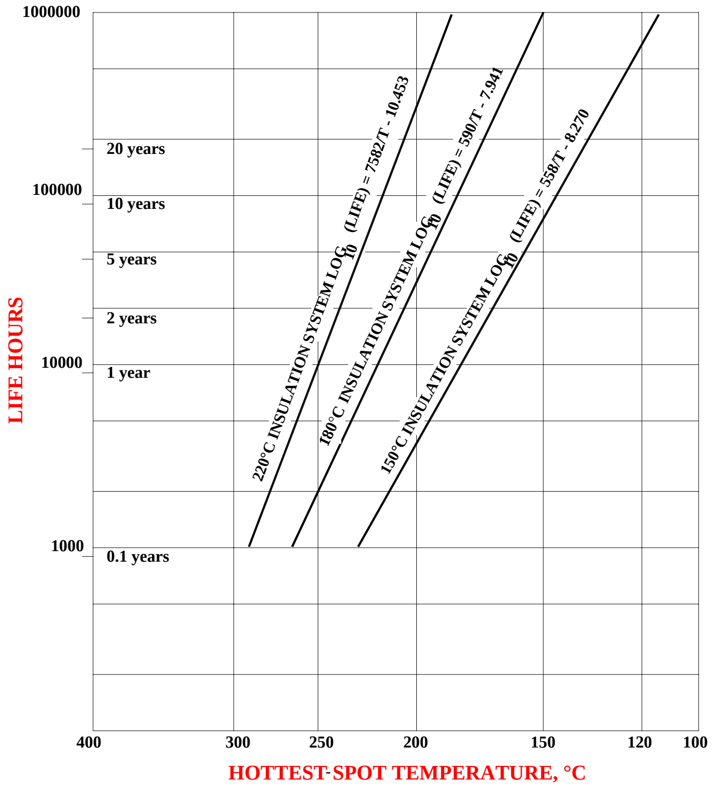

Figure 1—Life expectancy curve—base 10

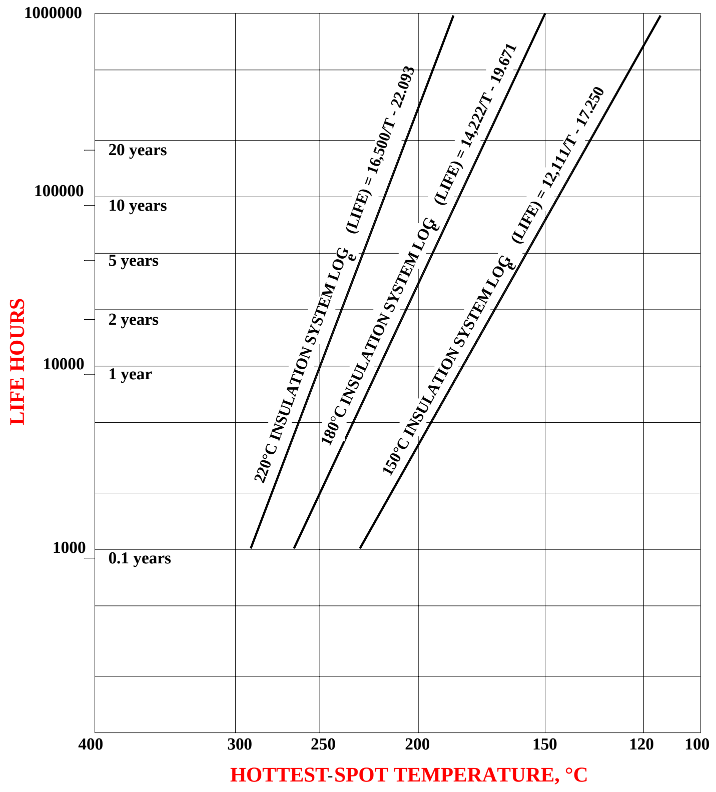

Figure 2—Life expectancy curve—base *e*

When the aging effect of one load cycle or the cumulative aging effect of a number of load cycles is greater than the aging effect of continuous operation at rated load over a given period of time, the insulation is deteriorated at a rate faster than normal. The rate of deterioration is a function of time and temperature, and may be expressed as a relative rate of aging for various hottest-spot winding temperatures. The reciprocal of the relative rate of aging is the relative life expectancy. The relative life expectancies shown in Figure 3 were used in the preparation of this guide.

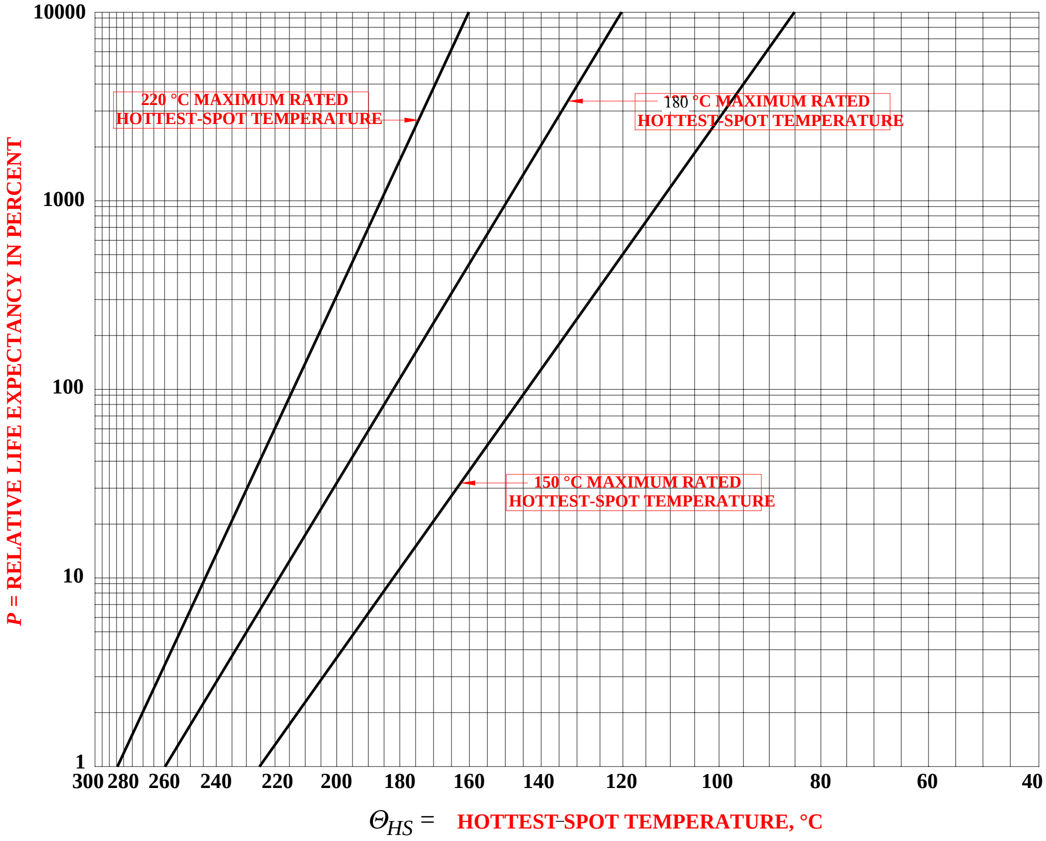

Figure 3—Relative life expectancy as a function of hottest-spot temperature

It should be clearly understood that, while the insulation aging rate information is considered to be conservative and helpful in estimating the relative loss of life due to loads above rating under various conditions, this information is not intended to furnish a basis for calculating the normal life expectancy of transformer insulation. Deterioration of insulation is generally characterized by a reduction in mechanical strength and in dielectric strength, but these characteristics may not necessarily be directly related. In some cases, insulation in a charred condition will have sufficient insulating qualities to withstand normal operating electrical and mechanical stresses. A transformer having insulation in this condition may continue in service for many months, or even years, if undisturbed. On the other hand, any unusual movement of the conductors, such as may be caused by expansion of the conductors due to heat resulting from a heavy overload or due to large electromagnetic forces resulting from a short circuit, may disturb the mechanically weak insulation so that turn-to-turn or layer-to-layer failure may result.

The uncertainty of service conditions is one of the reasons why this loading guide is conservative in its suggested loading schedule. As a guide, an average loss of life of 1% per year due to overloading, in addition to normal loss of life at rated load, is considered reasonable.

4.3 Constant loads and life expectancy estimated by measured temperature

When measured winding temperatures are known and when the load is constant [or when the actual load cycle can be reduced to an equivalent constant load without peaks by means of Equation (3)], loads and life expectancy may be estimated by the methods outlined in this subclause.

4.3.1 Relative life expectancy

The relative life expectancy in percent, P, for a constant load and measured temperature may be determined as follows:

a) When the hottest-spot winding conductor temperature, Θ_{HS}, is known, read the relative life expectancy directly from Figure 3.

   Example:
   For a 150 °C maximum hottest-spot transformer, assume the load and ambient temperature is such that the actual hottest-spot temperature is 130 °C. From Figure 3, the relative life expectancy is 200%.

b) When the hottest-spot temperature rise, $\Delta\Theta_{HS}$, is known and when the ambient, Θ_{a1}, is also known, calculate Θ_{HS} using Equation (5). From Figure 3, read the relative life expectancy that corresponds to the calculated hottest-spot temperature, Θ_{HS}.

   Example:
   For a ventilated dry-type unit with a 150 °C maximum hottest-spot allowance, assume that the ambient, Θ_a, equals 30 °C, the constant load equals 90% ($L_1 = 0.9$), and that the user's loading data show that the hottest-spot temperature rise, $\Delta\Theta_{HS}$, equals 93 °C when the load is 90%.

   1) $\Theta_{HS} = 30 + 93 = 123$ °C;
   2) From Figure 3, $P = 400\%$.

4.3.2 Constant load

The constant load permitted for a selected relative life expectancy in percent, P, may be determined when the hottest-spot winding conductor temperature, Θ_{HS}, versus load is known.

a) Select the desired relative life expectancy in percent, P, and determine Θ_{HS1} from Figure 3.
b) From the user's load data of Θ_{HS} versus load, select the load that will give Θ_{HS1} from Figure 3.

   Example:
   For a ventilated dry-type unit, assume that the user desires 70% of normal life expectancy ($P = 70\%$):

   1) From Figure 3, $\Theta_{HS1} = 145$ °C;
   2) From the user's load data of θ vs. load, select whatever constant load will give $\Theta_{HS1} = 145$ °C.

The values of Θ_{HS} will vary with the ambient temperature, Θ_a, and the permissible load will vary with changes in the ambient temperature. As long as Θ_{HS} for a given load does not exceed the values determined by the means outlined in this subclause, the given load will yield a life expectancy of no less than the selected life expectancy.

4.4 Constant loads and life expectancy estimated by calculated temperatures

When only the ambient temperature, Θ_a, and the hottest-spot winding temperature rise, $\Delta\Theta_{HS}$, at 100% load are known, and when the load is constant [or can be reduced to an equivalent constant load without peaks by means of Equation (3)], the loads and life expectancy may be estimated by the methods in this subclause.

The relative life expectancy in percent, *P*, for a constant load and calculated temperature may be determined as follows:

a) Estimate the hottest-spot winding temperature, Θ_{HS}, using Equation (5), Equation (6), and Equation (7).

b) For Θ_{HS}, calculated in item (a) above, select *P* from Figure 3.

Example:
Assume a ventilated dry-type transformer with the following conditions:

Θ_{a0} = 30 °C

$\Delta\Theta_{HS0}$ = 110 °C

Θ_{HS0} = 140 °C at 100% load or at $L_0 = 1$

To determine the relative life expectancy that will result from continuous operation at 105% load in a 25 °C ambient, perform the following:

1) From Equation (7):
   $\Delta\Theta_{HS2} = 110 \times [(1.05/1.00)]^{1.6}$
   $\Delta\Theta_{HS2}$ = 119 °C
2) From Equation (5):
   Θ_{HS1} = 25 + 119 = 144 °C
3) From Figure 3:
   P = 75% for Θ_{HS1} = 144 °C

The constant load permitted for a selected relative life expectancy may be calculated by reversing the sequence of the steps in the preceding example.

4.5 Short-time loading and life expectancy determined by measured temperatures

When measured hottest-spot temperatures are known for various loads and when the actual load cycle cannot be reduced to a constant load, the methods outlined in this subclause may be used to estimate permissible loads and life expectancy.

The relative life expectancy in percent, *P*, for an initial equivalent constant load followed by an equivalent constant peak load may be determined as follows, using measured temperatures:

a) Reduce the actual load cycle to an equivalent load cycle by the method given in 6.1. This equivalent load cycle should consist of an equivalent constant load, L_1, of duration t_1, followed by an equivalent constant peak load, L_2, of duration t_2.

b) From the user's measured load versus temperature data, determine the hottest-spot winding conductor temperature, Θ_{HS1} for L_1 and Θ_{HS2} for L_2, directly or by means of Equation (5), Equation (6), and Equation (7). Θ_{H1} is the steady-state hottest-spot temperature for L_1; it is also the initial hottest-spot temperature, Θ_{HS1}, for the transient occurring during the peak load, L_2. Θ_{HSu} is the ultimate, or steady-state, hottest-spot temperature for L_2.

c) Using exponential transient paper (see Figure 4), plot the measured initial hottest-spot temperature, Θ_{HS1}, on the left ordinate and the measured ultimate hottest-spot temperature, Θ_{HSu} , on the right ordinate. Connect the two by a straight line.

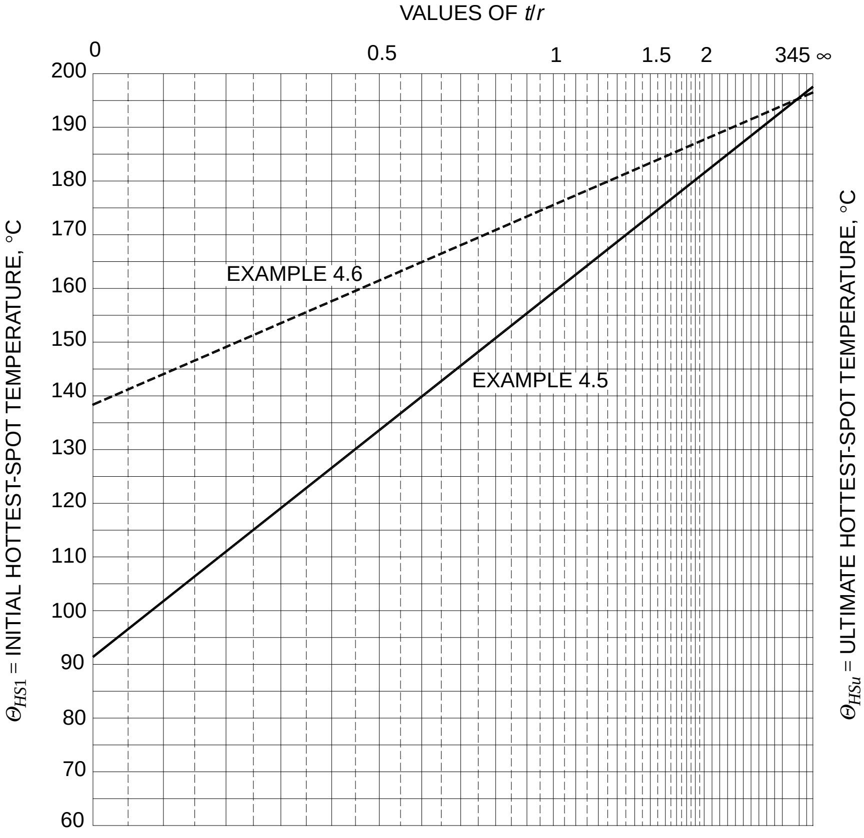

Figure 4—Hottest-spot temperature as a function of time

d) Using the measured time constant, t, of the transformer and the duration of the peak load, t_2, determine t_2/t and read the peak load temperature, Θ_{HS2}, from Figure 4 as prepared in item (c) above.

e) From Figure 3, determine the relative life expectancies in percent: P_1 for Θ_{HS1} and P_2 for Θ_{HS2}.

f) The relative life expectancy resulting from such a load cycle repeated every $t_1 + t_2$ hours during the operation of transformers is

$$P_r = (t_1 + t_2)/[(t_1/P_1) + (t_2/P_2)] \qquad (2)$$

Example:

Assume a ventilated, self-cooled, dry-type transformer having a load cycle that can be reduced (as shown in 6.1) to an equivalent load: $L_1 = 0.7$ for $t_1 = 22$ h, followed by a peak of $L_2 = 1.25$ for $t_2 = 2$ h. The ambient Θ_{a1} equals 29 °C and the ambient Θ_{a2} equals 40 °C. The user's loading data show the time constant, $t = 1.3$ h, and the measured hottest-spot rises for the two loads are

$L_1 = 0.7$, $\Delta\Theta_{HS1} = 62$ °C

and

$L_2 = 1.25$, $\Delta\Theta_{HS2} = 158$ °C

Determine the relative life expectancy if the above cycle occurs daily:

1) From Equation (5) and item (b):
   Θ_{HS1} = 29 + 62 = 91 °C
   Θ_{HSu} = 40 + 158 = 198 °C.
2) See item (c), Figure 5, and Figure 6.
3) From item (d), $f(t_2/t) = f(2/1.3) = 1.54$ and Θ_{HS2} = 175 °C.
4) From item (e) and Figure 3:
   P_1 = 3700% for Θ_{HS1} = 91 °C
   P_2 = 12% for Θ_{HS2} = 175 °C.
5) From item (f):
   $P = (22 + 2)/[(22/3700) + (2/12)] = 139\%$.

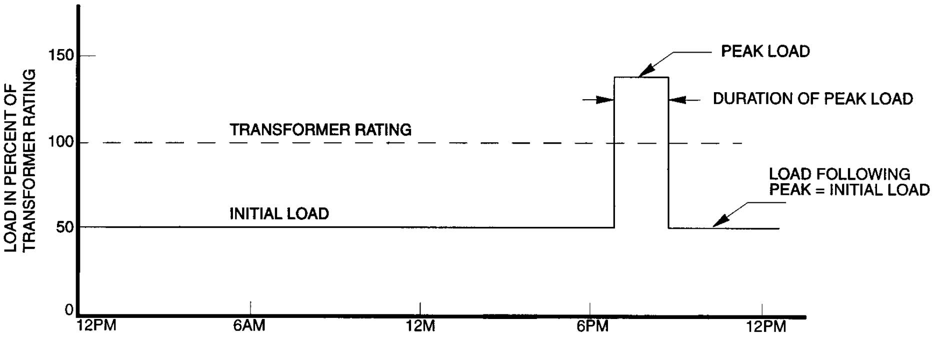

Figure 5—Assumed load cycle

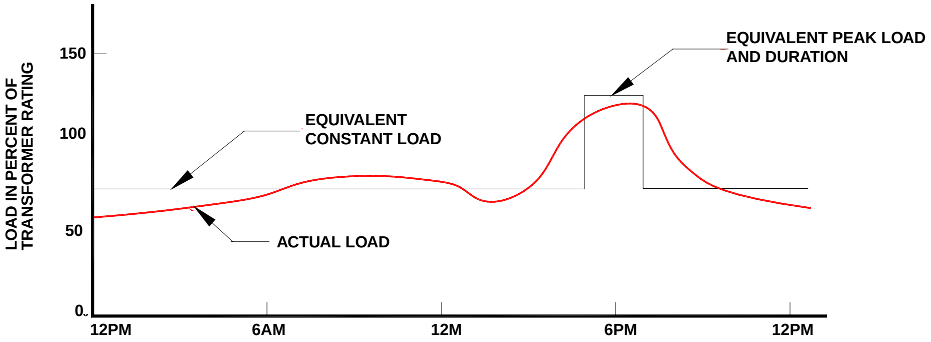

Figure 6—Actual load cycle

Many combinations of constant loads followed by short-time peak loads may be chosen to give a selected life expectancy. In order to determine load cycles to give a particular life expectancy, it is necessary to reverse the sequence of the steps in 6.1, beginning with a selected resultant relative life expectancy, *P*, and assuming combinations of P_1, P_2, t_1, and t_2.

4.6 Short-time loading and life expectancy estimated by calculated temperatures

When only the ambient temperature, Θ_{a1}, and the hottest-spot winding temperature rise at 100% load, $\Delta\Theta_{HS}$, are known, and when the actual load cycle cannot be reduced to a constant load, the methods outlined in this subclause may be used to estimate permissible loads and life expectancy.

The relative life expectancy in percent, P, for an initial equivalent constant load followed by an equivalent constant peak load may be determined as follows, using calculated temperatures:

a) Reduce the actual load cycle to an equivalent cycle by the method given in 6.1. This equivalent should consist of an equivalent constant per unit load, L_1, of duration t_1, followed by an equivalent constant peak load, L_2, of duration t_2.

b) Calculate the hottest-spot winding conductor temperatures: Θ_{HS1} for L_1 and Θ_{HSu} for L_2, using Equation (5). Θ_{HS1} is the steady-state hottest-spot temperature for L_1; it is also the initial hottest-spot temperature, Θ_{HS1}, for the transient occurring during the peak load, L_2. Θ_{HSu} is the ultimate hottest-spot temperature for L_2.

c) Using exponential transient paper (see Figure 4), plot the calculated initial hottest-spot temperature, Θ_{HSi}, on the left ordinate and the calculated ultimate hottest-spot temperature, Θ_{HSu}, on the right ordinate. Connect the two by a straight line.

d) Determine the time constant of the transformer, T, using Equation (8). Then using the duration, t_2, of the peak load, L_2, determine t_2/T and read the peak load temperature, Θ_{HS2}, from the transient curve prepared in item (c) above.

e) From Figure 3, determine the relative life expectancies in percent: P_1 for Θ_{HS1} and P_2 for Θ_{HS2}.

f) The relative life expectancy resulting from such a load cycle repeated every $t_1 + t_2$ hours during the life of the transformer can be calculated using Equation (2).

Example:
Assume a ventilated self-cooled, dry-type transformer with copper windings and having a load cycle that can be reduced by the method given in 6.1 to an equivalent per unit load: $L_1 = 1.0$ for $t_1 = 364$ days + 16 h, followed by an equivalent constant peak load, $L_2 = 1.25$ for $t_2 = 8$ h. Assume an average ambient of $\Theta_{a1} = 29$ °C and $\Theta_{a2} = 40$ °C, a reported hottest-spot rise by resistance at 100% load of $\Delta\Theta_{HS} = 110$ °C, and assume that no measured temperature versus load data are available. From the reported tests, the total loss at 100% load is $W = 3600$ and, from the nameplate, the core and coil weight is 2042 kg. Determine the life expectancy for the above cycle repeated yearly.

1) From item (b) and Equation (7):

   $\Delta\Theta_{HS1} = 110\ [(1.0/1.0)]^{1.6} = 110$ °C

   $\Delta\Theta_{HS2} = 110\ [(1.25/1.0)]^{1.6} = 157$ °C.

2) From item (c) and Equation (5):

   $\Theta_{HS1} = 29 + 110 = 139$ °C

   $\Theta_{HS2} = 40 + 157 = 197$ °C.

3) See item (d) and the line for Example 4.6 in Figure 4.

4) From item (e) and Equation (8):

   $t = (0.033 \times 2042 \times 80)/3600 = 1.5$,

   then $t_2/t = 8/1.5 = 5.33$; $\Theta_{HS2} = 197$ °C.

5) From item (e) and Figure 3:

   P_1 = 103% for Θ_{HS1} = 139 °C

   P_2 = 4% for Θ_{HS2} = 197 °C.

6) From item (f):

   $P_r = [(364 \times 24 + 16) + 8]/[\{[(364 \times 24) + 16]/103\}+(8/4)] = 8760/[(8752/103) + (8/4)]$

   P_r = 100.5% life expectancy.

5. Supplemental cooling of existing self-cooled transformers

The load that can be carried on existing self-cooled transformers can be increased considerably by the addition of auxiliary cooling equipment such as fans. The amount of additional loading varies widely depending on the following:

a) Design characteristics of the transformer;
b) Type of cooling equipment;
c) Permissible increase in voltage regulation;
d) Limitations of associated equipment.

No general guides can be given for such supplemental cooling, and each transformer, depending on whether it is a sealed or ventilated type, should be considered individually.

6. Basis for calculations of temperatures, loss of life, and loads

An outline of methods that may be used to determine short-time loads with no sacrifice of life expectancy is given in 3.2. Methods for determining constant loads and short-time loads with moderate sacrifice of life are given in Clause 4. All the methods given in the preceding clauses are based on the equations, assumptions, and empirical data presented here, which give results that are of the right order of magnitude and that are in general agreement with tests and data from several independent sources.

6.1 Method for converting actual load cycle to equivalent constant load

Permissible loading, as obtained from Table 4, Table 5, and Table 6, is a function of the initial load, the peak load, and their duration. Each loading combination in Table 4, Table 5, and Table 6 may be considered as a simple rectangular load cycle consisting of an essentially constant initial load of 50%, 70%, or 90% of rating, followed by a rectangular peak of the magnitude and time as given in the tables, and with the load returning to the initial load at the end of the rectangular peak. The assumed loading for the calculations in the tables is illustrated in Figure 5.

Ordinarily, the daily load cycle is not so simple, but more often is like the cycle represented by the solid line in Figure 6 throughout the day, and usually with one period in the daily load cycle when the load builds up to a considerably greater value than any reached at other times. Generally, the maximum value or peak load is not reached and passed suddenly, but builds up and falls off gradually.

To use the loading recommendations, the actual fluctuating load cycle must be converted to a thermally equivalent, simple rectangular load cycle such as represented by the dashed line in Figure 6. A transformer supplying a fluctuating load generates a fluctuating loss, the effect of which is about the same as that of an intermediate load held constant for the same period of time. This is due to the heat storage characteristics of the materials in the transformer. A load, generating losses at the same rate as the average rate caused by the fluctuating load, is an equivalent load from a temperature standpoint. Equivalent load for any portion of a daily-load cycle may be expressed by Equation (3).

$$L_{EQ} = [(L_1^2 t_1 + L_2^2\ t_{\ 2} + \ldots + L_n^2\ t_{\ n})/(t_1 + t_2 + \ldots + t_n)]^{0.5} \tag{3}$$

where

$L_1, L_2, \ldots, L_\mathrm{n}$	are various load steps in percent, per unit, in actual kilovolt-amperes or current,
$t_1, t_2, \ldots, t_n$	are the duration of these loads, respectively.

Equivalent initial load is the root-mean-square (rms) load obtained by Equation (3) over a chosen period preceding the peak load. Experience with this method of load studies indicates that quite satisfactory results are obtained by considering the 12 h period preceding the peak in the determination of the equivalent initial load. Time interval *(t)* of 1 h is suggested as a further simplification of the equation that, for a 12 h period, becomes the following:

$$\text{equivalent initial load} = 0.29\ (L_1^2 + L_2^2 + \ldots + L_{12}^2)^{0.5} \tag{4}$$

where L_1, L_2,…, L_{12} are the average load by inspection for each 1 h interval of the 12 h period preceding peak load.

Equivalent peak load for the usual load cycle is the rms load obtained by Equation (3) for the limited period over which the major part of the actual irregular peak seems to exist. The estimated duration of the peak has considerable influence over the rms peak value. If the duration is overestimated, the rms peak value may be considerably below the maximum peak demand. To guard against overheating due to high, brief overloads during the peak period, the rms value for the peak load should not be less than 90% of the integrated 1/2 h maximum demand.

This method may be used to convert an irregular load cycle, as in Figure 6, to a rectangular load cycle. In this case, the continuous portion is 70% and the peak is 125% of rated kilovolt-amperes for 2 h. Table 5 shows that for a transformer with a 150 °C insulation system in a 20 °C ambient, the permissible load following a continuous load of 70% is 129%. Therefore, the transformer can carry this load cycle daily without sacrifice of normal life expectancy.

6.2 Equations for calculation of temperature, load, and loss of life

6.2.1 List of symbols

The following symbols and terms are used in this subclause:

Θ, with any subscript, is temperature, in °C;

Θ_a is the ambient temperature;

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

$\Delta\Theta_{HS}$ is the hottest-spot winding temperature rise above ambient, in °C;

τ is the time constant, in hours, for the transformer at rated load, approximately equal to the time required to reach 63% of final temperature;

m is an empirical constant; for ventilated, self-cooled dry type, $m = 0.8$; for forced-cooled dry type, $m = 1.0$; for sealed self-cooled dry type, $m = 0.7$;

T is absolute temperature, i.e., $\theta + 273$ K;

C is the thermal capacity of the transformer, in watt-hours per °C;

t is the duration of load, in hours;

W_r is the winding watts loss at rated load with a 20 °C ambient;

L is per unit load;

E is the life expended, in years;

E_r is the life expended when operated at rated conditions;

A and B are constants for the Arrhenius equation;

P is the relative life expectancy, in percent, $(E/E_r) \times 100$;

Subscript r indicates rated load, normal life, or rated temperature;

Subscripts 1, 2, 3, etc., indicate any other load, temperature, or time;

Subscript i indicates initial load, temperature, or time for transients;

Subscript u indicates ultimate load, temperature, or time for transients;

Example:

Θ_{HSr} is the hottest-spot winding temperature at rated load.

6.2.2 Calculation of transient temperature

The hottest-spot winding temperature is

$$\Theta_{HS} = \Theta_a + \Delta\Theta_{HS} \tag{5}$$

The initial hottest-spot rise gradient is

$$\Delta\Theta_{HS} = \Delta\Theta_{HSr}\, [L]^{2m} \tag{6}$$

The average winding rise is

$$\Delta\Theta_{HS2} = \Delta\Theta_{HSr}\, [(L_1/L_r)]^{2m} \tag{7}$$

The time constant at rated load is

$$t = (C\Delta\Theta_{HSr}/W_r) \tag{8}$$

where

$C = 0.106 \times$ weight of copper winding, or

$C = 0.033 \times$ weight of core and copper windings from the nameplate.

$C = 0.260 \times$ weight of aluminum windings, or

$C = 0.044 \times$ weight of core and aluminum coils from the nameplate.

$$\Theta_t = (\Delta\Theta_u - \Delta\Theta_i)\,(1 - e^{-t/t}) + \Theta_i. \tag{9}$$

6.2.3 Calculation of life expended during time interval *t*

$$E = t_{10}^{\;-A_{10} + (B_{10}/T)} \tag{10}$$

or

$$E = t_e^{\;-A_e + (B_e/T)}$$

where A and B are the constants from the life expectancy curve. The loss of life for each interval can then be summed over the 24 h cycle.

For 1440 min of aging in a 24 h period, the values of A and B are as follows:

Insulation system	A_{10}	B_{10}	A_e	B_e
150 °C	–8.270	5581	–17.250	12 111
180 °C	–7.941	5907	–19.671	14 222
220 °C	–10.453	7582	–22.093	16 500

These values were developed from Figure 1 and Figure 2 based on a normal life expectancy of 20 y.

NOTE—These equations assume Θ_{HS} for each interval t to be continuous for the entire interval, so incremental time intervals for any load should be selected that are small enough to avoid serious error.

6.2.4 Corrections for equations

Theoretically, several corrections should be made when using the foregoing equations, such as corrections for change in

a) Time constant for loads other than rated load;

b) Ultimate winding conductor loss at the end of a long period.

In making general calculations based on assumptions of transformer characteristics and maximum hottest-spot temperature that are generally conservative, results close enough for all practical purposes are obtained if all these corrections are omitted and the simpler formulae are used.

6.2.5 Time constant

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 limited data available for dry-type transformers indicate that transient temperatures may be calculated conservatively on the basis of these assumptions.

The time constant is the length of time that would be required for the hottest-spot temperature of the winding to change from the initial value to the ultimate value if the initial rate of change were continued until the ultimate temperature was reached.

The time constant may also be expressed as the length of time required for a specified percentage of the change in temperature to take place from initial value to ultimate value.

If m (the exponential power of temperature rise versus loss) equals unity, 63% of the temperature change occurs in a length of time equal to the time constant, regardless of the relationship of initial temperature and ultimate temperature rise.

If m is equal to 1, Equal 9 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 cooling cycle is given by the following:

$$\tau = \tau_0 \, [(\Delta\Theta_{HSU}/\Delta\Theta_{HS0}) - (\Delta\Theta_{HSI}/\Theta_{HSO})]/[(\Delta\Theta_{HSU}/\Delta\Theta_{HSO})^{1/m} - (\Delta\Theta_{HSI}/\Delta\Theta_{HSO})^{-1/m}] \qquad (11)$$

6.3 Transient computer program

The computer program using BASIC language, developed to calculate data for Table 4, Table 5, and Table 6, is as follows. Time intervals of 1 min were used to improve accuracy of calculations, and the resultant aging is given in days.

```
100    PRINT "EQUIVALENT AGING OF TRANSFORMER COMPUTER PROGRAM"
110    PRINT "THIS PROGRAM IS DESIGNED TO FIND THE DRY-TYPE AGING OF A"
111    PRINT "DRY-TYPE TRANSFORMER OVER A ONE-DAY PERIOD OF TIME. THE TRANSFORMER"
112    PRINT "IS LOADED TO SOME INITIAL VALUE LESS THAN 100 PERCENT UNTIL"
113    PRINT "ITS TEMPERATURE EQUILIBRIUM POINT IS REACHED. THEN THE TRANS-"
114    PRINT "FORMER IS LOADED GREATER THAN 100 PERCENT FOR SOME CHOSEN"
115    PRINT "PERIOD OF TIME. THE LOAD IS THEN REDUCED TO THE ORIGINAL"
116    PRINT "VALUE."
117    PRINT "THIS PROGRAM CAN ENABLE ONE TO DETERMINE, FOR A GIVEN OVER-"
118    PRINT "LOAD PERIOD, WHAT VALUE THE TRANSFORMER MAY BE OVERLOADED AND"
119    PRINT "THEN ALLOWED TO RETURN TO THE INITIAL LOAD WITHOUT EXCEEDING"
120    PRINT "THE EQUIVALENT AGING. THIS EQUIVALENT AGING IS THE AMOUNT"
121    PRINT "A TRANSFORMER WOULD UNDERGO IN A ONE-DAY PERIOD AT 100 PER-"
122    PRINT "CENT CONTINUOUS LOAD IN A 30 DEGREE AMBIENT."
130    PRINT "PARAMETERS ARE AS FOLLOWS:"
131    PRINT "A AND B VALUES ARE EMPIRICAL AS DETERMINED BY ARRHENIUS"
132    PRINT "EQUATION BASE 10 FOR A GIVEN INSULATION SYSTEM."
133    PRINT "C = RATED HOTTEST-SPOT TEMPERATURE RISE"
134    PRINT "DELT = 1 (MINUTE)"
135    PRINT "T = TIME (MINUTES)"
136    PRINT "TAU = TIME CONSTANT (MINUTES)"
```

```
137    PRINT "AMB = AMBIENT TEMPERATURE"
138    PRINT "LI = INITIAL LOAD LESS THAN 1.0"
139    PRINT "LU = OVERLOAD GREATER THAN 1.0"
140    PRINT "X = PERIOD OF TIME IN MINUTES THAT OVERLOAD OCCURS"
141    PRINT "RA = AGING FACTOR FOR DELT PERIOD OF TIME"
142    PRINT "SUMRA = SUMMATION OF AGING FACTORS FOR 1440 MINUTES (ONE DAY)"
143    PRINT "WHEN SUMRA = 1, THEN EQUIVALENCY TO AGING FOR ONE DAY OPERATION"
144    PRINT "AT 100 PERCENT LOAD IS OBTAINED."
145    PRINT "TEMPI = INITIAL TEMP RISE DUE TO CONSTANT LOAD < 1.0"
146    PRINT "TEMPU = ULTIMATE TEMP RISE TRANSFORMER WOULD REACH IF OVERLOAD WERE"
147    PRINT "CONTINUOUSLY APPLIED."
148    PRINT "TEMPR = TEMPERATURE RISE OF TRANSFORMER FOR ONE SPECIFIC VALUE OF TIME."
149    PRINT "NOTE: WHEN TEMPR IS PRINTED, IT IS THE VALUE AT THE END OF OVERLOAD."
150    PRINT "ABST = ABSOLUTE TEMPERATURE"
151    PRINT "TEMPF = FINAL TEMPERATURE TRANSFORMER DECAYS TO 1440 MINUTES"
200    INPUT; "A,B,C,TAU,AMB"; A,B,C,TAU,AMB
210    INPUT; "LI = "; LI
220    INPUT; "X = "; X
230    INPUT; "LU = "; LU
240    T = 0
245    DELT = 1
250    SUMRA = 0
260    TEMPI = LI^1.6 * C
270    PRINT "TEMPI = "; TEMPI
280    TEMPU = LU^1.6 * C
290    PRINT "TEMPU = "; TEMPU
292    TAU1 = TAU*((TEMPU – TEMPI)/((TEMPU^1.25) – (TEMPI^1.25))) * C^0.25
300    T = X
302    RD = EXP(–1 * T/TAU1)
304    RE = 1 – RD
```

```
310    TEMPR = (TEMPU – TEMPI) * RE + TEMPI
312    TAU2 = TAU * ((TEMPI – TEMPR)/((TEMPI^1.25) – (TEMPR^1.25))) * C^0.25
313    T = 0
314    FOR T = 0 TO X
315    RD = EXP (–1 * T/TAU1)
316    RE = 1 – RD
317    TEMPR = (TEMPU – TEMPI) * RE + TEMPI
320    ABST = TEMPR + 273 + AMB
322    RB = –1 * (A+B/ABST)
324    RC = 10^RB
330    RA = 122 * DELT * RC
340    SUMRA = SUMRA + RA
345    NEXT T
360    FOR T = X TO 1440
362    RF = –1 * (T – X)/TAU2
364    RG = EXP(RF)
366    RH = 1 – RG
370    TEMPF = (TEMPI – TEMPR) * RG + TEMPR
380    ABST = TEMPF + 273 + AMB
382    RB = –1 * (A + B/ABST)
384    RC = 10^RB
390    RA = 122 * DELT * RC
400    SUMRA = SUMRA + RA
410    NEXT T
420    PRINT "TEMPR = "; TEMPR
430    PRINT "TEMPF = "; TEMPF
440    PRINT "SUMRA = "; SUMRA
442    PRINT "TAU1 = "; TAU1
444    PRINT "TAU2 = "; TAU2
450    GO TO 230
```

7. Protective devices—thermal relays

A transformer thermal relay is a device, the operation of which indicates that predetermined time-temperature limits in the transformer windings have been reached. It is calibrated for use with specific transformer apparatus and automatically takes into account the hottest-spot temperature of the windings, the ambient temperature, and previous conditions of loading. Higher loads are permitted for short periods of operation than for long periods of operation.

The relay can be adjusted to give indication at loads that can produce practically normal life expectancy or some predetermined moderate sacrifice of such expectancy.

The device has one or more contacts that may be used for various functions, such as starting fans, giving a signal or an alarm, or disconnecting the transformers.

Annex A

(normative)

Power transformers with solid-cast and/or resin-encapsulated epoxy windings

A.1 Overview

This part of the guide covers general recommendations for the loading of ventilated dry-type distribution and power transformers with solid-cast and/or resin-encapsulated epoxy windings manufactured in accordance with IEEE Std C57.12.01-1998[5] with continuous ratings. It covers insulation systems limited to 130 °C, 150 °C, and 180 °C maximum hottest-spot operating temperatures at rated output in a 40 °C maximum ambient.

The recommendations given in this guide are based solely on the thermal characteristics of cast-resin transformers. 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 leads, connections, tap terminal boards, and the thermal capability of associated 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 rating. These may constitute the practical limit on load-carrying ability and should be considered before applying loads in excess of rating.

This guide covers applications where harmonic currents do not exceed the limits given in IEEE Std C57.12.01-1998. IEEE Std C57.110-1998 should be consulted for recommended practice for establishing transformer capability when supplying nonsinusoidal load currents.

If the user desires more specific recommendations for a particular transformer, the manufacturer of that transformer should be consulted. For transformers that do not have a continuous rating, the manufacturer should be consulted for additional information when such information is not indicated on the nameplate.

A.2 References

This annex shall be used with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std C57.12.01-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid Cast and/or Resin-Encapsulated Windings.[6]

IEEE Std C57.12.59-1989, IEEE Guide for Dry-Type Transformer Through-Fault Current Duration.[7]

IEEE Std C57.12.60-1998, IEEE Guide for Test Procedures for Thermal Evaluation of Insulation Systems for Solid-Cast and Resin-Encapsulated Power and Distribution Transformers.

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[5] Information on references in this annex can be found in A.2.

[6] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

[7] IEEE Std C57.12.59-1989 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

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.

A.3 Definitions

A.3.1 cast-resin transformer: A ventilated dry type distribution or power transformer with solid-cast and/or resin-encapsulated epoxy windings.

A.3.2 loading above rating: Short-time loading in excess of the nameplate rating which results in hottest-spot temperatures exceeding the insulation temperature class.

A.3.3 rated kilovolt-ampere output: The load, in amperes, that a cast-resin transformer can deliver continuously at rated secondary voltage and rated frequency without exceeding the specified hottest-spot temperature or average winding temperature rise under usual service conditions, as described in Clause 4 of IEEE Std C57.12.01-1998. *Synonyms:* rated output, rated load, nameplate rating.

A.3.4 rated temperature loading: Short-time loading in excess of the nameplate rating with hottest-spot temperatures below or equal to the insulation temperature class.

A.4 Insulation aging

Current practice by manufacturers has been to rely on tests of individual materials to determine the rated insulation temperature class to assign to their designs. Operating experience indicates that this gives acceptable life when cast-resin transformers are operated at nameplate ratings. At the present time, industry has not established Arrhenius insulation aging curves to give loss of insulation life for cast-resin transformer windings operated above the rated insulation temperature class.

IEEE Std C57.12.60-1998, which covers thermal evaluation of insulation systems for solid cast-resin transformers, will serve as a standard test method for determining the rated insulation temperature class of cast-resin transformer windings. The materials and coil design techniques used in cast-resin transformers necessitated a document to recognize factors such as the effect of glass transition temperature, higher resin-to-air and metal ratios, filler contents, and conductor identity on aging and performance. An arbitrary extrapolation criteria of 40 000 h was selected for the evaluation. The thermal evaluation standard was first issued as a trial-use document to permit manufacturers to conduct life test programs on models or full-size windings to obtain experience with the standard. In addition to determining the rated insulation temperature class, thermal evaluation standards give data for preparing loading guides. At the time this loading guide was approved, no test data in accordance with IEEE Std C57.12.60-1998 had been reported. The effect of cracking or softness of the epoxy due to thermal cycling to elevated temperatures could be the limiting factor in overloading cast-resin transformers and not insulation aging. Due to the lack of data, this guide for loading cast-resin transformers used a concept based on limiting hottest-spot temperatures to determine loading capability of cast-resin transformers.

A.5 Temperature limits for loading

The actual output that a cast-resin transformer can deliver at any time in service may be more or less than the rated kilovolt-ampere output, depending upon the ambient temperature, altitude, and other attendant operating conditions. If the load and ambient temperatures are below rated, then an overload may be sustained until the hottest-spot temperature reaches the temperature of the insulation class of the windings. This is described as *rated temperature loading* and should give normal life expectancy. Loading that results in hottest-spot temperatures above the insulation temperature class was defined as *loading above rating*. Loading above rating can result in reduced life expectancy. The life expectancy decreases due to the total cumulative effect of operation at a hottest-spot temperature above rating and the time at elevated hottest-spot temperature. The manufacturer should be consulted for recommendations for maximum permissible hottest-spot temperatures for loading above rating.

Table A.1—Temperature limits for loading

Insulation temperature class, °C	Maximum hottest-spot temperature, °C rated temperature loading	Maximum hottest-spot temperature, °C loading above rating
130	130	165
150	150	180
180	180	220

A.6 Ambient temperatures

Ambient temperature is an important factor in determining the load capability of a cast-resin transformer because the hottest-spot rise for any load must be added to the ambient to determine the operating temperature. 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. The operation of transformers in cooling air above 50 °C, or below –30 °C, is not covered by this guide and should be checked with the manufacturer.

It is intended that cast-resin transformers be installed based on the recommendations given in IEEE C57.94-1982. If cast-resin transformers are installed in subsurface vaults or enclosures of minimum size where the natural ventilation is insufficient to prevent marked changes in the 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.

Whenever the actual ambient temperature can be determined from readings taken at the time of the load being considered, such temperatures should be used to determine the hottest-spot temperature and the load capability of the transformer. It is often necessary to predict the load that a transformer can carry 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. These reports are available for areas throughout the world.[8] These ambients should be used as follows:

a) For rated temperature loading, use the average temperature over a period of years for the month involved.

b) For loading above rating, 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.

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

c) 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.

A.7 Influence of altitude on loading

The effect of the decreased air density due to high altitude is to increase the temperature rise of cast-resin transformers since they are dependent upon air for dissipation of heat loss. Cast-resin transformers may be operated at rated kilovolt-amperes at altitudes greater than 1000 m (3300 ft) without exceeding hottest-spot temperature limits, provided the average temperature of the cooling air does not exceed the values of Table A.2 for the respective altitudes.

Cast-resin transformers may be operated in a 30 °C ambient at altitudes greater than 1000 m (3300 ft) without exceeding hottest-spot temperature limits, provided the load to be carried is reduced below rating by the percentages given in Table A.3 for each 100 m (330 ft) that the altitude is above 1000 m (3300 ft).

Table A.2—Maximum allowable 24 h average temperature of cooling air, in °C, for operation at rated kVA under unusual temperature and altitude conditions

Insulation temperature class, °C AA cooling	**ALTITUDE**			
	1 000 m (3 300 ft)	**2 000 m (6 600 ft)**	**3 000 m (9 900 ft)**	**4 000 m (13 200 ft)**
130	30	28	26	24
150	30	26	22	18
180	30	24	18	12
Insulation temperature class, °C FA cooling	**ALTITUDE**			
	1 000 m (3 300 ft)	**2 000 m (6 600 ft)**	**3 000 m (9 900 ft)**	**4 000 m (13 200 ft)**
130	30	26	21	17
150	30	22	14	6
180	30	18	7	–5

Table A.3—Rated kVA derating factors for altitudes greater than 1000 m (3300 ft) at 30 °C average ambient temperature

Type of cooling	**Derating factor (%) for each 100 m (330 ft)**
Self-cooled (AA)	0.3
Forced-air-cooled (FA)	0.5

A.8 Loading equations

A.8.1 Continuous loading

The hottest-spot temperature rise as a function of load for steady-state conditions may be calculated by the following equations:

$$\Theta_{HS} = \Theta_a + \Delta\Theta_{HS} \tag{A.1}$$

Self-cooled operation:

$$\Delta\Theta_{HS} = \Delta\Theta_{HS,r}[L]^{2m} \tag{A.2}$$

Fan-cooled operation:

$$\Delta\Theta_{HS} = \Delta\Theta_{HS,r}[L^2K_T]^X \tag{A.3}$$

$$K_T = \frac{T_k + \Theta_{HS}}{T_k + \Theta_{HS,r}} \tag{A.4}$$

where

$\Delta\Theta_{HS}$	is the hottest-spot temperature rise over ambient at per unit load *L*, 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 [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,
K_T	is the temperature correction for resistance change with temperature,
m	is an empirical constant, which is equal to 0.8 (suggested unless test data is available),
Θ_a	is the ambient temperature, in °C,
Θ_{HS}	is the hottest-spot temperature at load *L*, in °C,
$\Theta_{HS,r}$	is the rated or tested hottest-spot temperature 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,
X	is an empirical constant used in forced-air calculation, which is 1.0 (suggested unless test data available).

Test data indicates that the above equations 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 (A.4) is required to predict hottest-spot temperatures during forced-air loading due to the higher losses present at forced-cooled operation.

Equation (A.2) and Equation (A.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 (A.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.

A.8.2 Transient loading

The hottest-spot temperature due to transient overloading may be determined by the following equations:

$$\Delta\Theta_t = (\Delta\Theta_U - \Delta\Theta_i)\left[1 - \exp^{-\frac{t}{\tau}}\right] + \Delta\Theta_i \tag{A.5}$$

$$\Theta_{HS} = \Delta\Theta_t + \Theta_a \tag{A.6}$$

where

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

$\Delta\Theta_t$ is the hottest-spot temperature rise at some time t after the overload, 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 is the time constant in minutes for the transformer at rated load,

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

Θ_a is the ambient temperature, in °C.

A.8.3 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 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, is

$$\tau_R = \frac{C(\Delta\Theta_{HS,r} - \Theta_e)}{P_r} \tag{A.7}$$

where

C is the effective thermal capacity of winding, in watt-minutes per °C,

= (15.0 × weight of aluminum conductor in kilograms) + (6.35 × weight of epoxy and other winding insulation in kilograms), or

= (6.42 × weight of copper conductor in kilograms) + (6.35 × weight of epoxy and other winding insulation in kilograms), or

= 11.2 × weight of aluminum windings in kilograms, or

= 6.39 × weight of copper windings in kilograms;

P_r is the I^2R loss of a winding at rated load and rated temperature rise, in watts;

$\Delta\Theta_{HS,r}$ is the winding hottest-spot temperature rise at rated load, in °C;

Θ_e is the core contribution to winding hottest-spot rise at rated load

= 0 for outer (primary) winding,

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

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).

$$\tau = \tau_{HS,r} \frac{\left(\frac{\Delta\Theta_U}{\Delta\Theta_{HS,r}}\right) - \left(\frac{\Delta\Theta_i}{\Delta\Theta_{HS,r}}\right)}{\left(\frac{\Delta\Theta_U}{\Delta\Theta_{HS,r}}\right)^{\frac{1}{m}} - \left(\frac{\Delta\Theta_i}{\Delta\Theta_{HS,r}}\right)^{\frac{1}{m}}} \qquad \text{(A.8)}$$

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 equations. Consideration may be given to specifying that time constants be shown on test reports when supplied.

A.8.4 Calculation of loading capability

Equations (A.1) through (A.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 (A.2) and is determined as follows:

$$\Delta\Theta_i = \Delta\Theta_{HS,r}[L_i]^{2m} \qquad \text{(A.9)}$$

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

$$\Delta\Theta_t = \Theta_{HS} - \Theta_A \qquad \text{(A.10)}$$

Determine the ultimate hottest-spot temperature rise from Equation (A.5).

$$\Delta\Theta_U = \left[\frac{\Delta\Theta_t - \Delta\Theta_i}{1 - \exp(-t/\tau)}\right] + \Delta\Theta_i \qquad \text{(A.11)}$$

The time constant τ 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:

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

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

A.8.5 Loading capability calculations

A.8.5.1 Loading on basis of ambient temperature

The continuous loading capability as a function of ambient temperature determined by the above equations is given in Table A.4. This loading capability was determined so that the hottest-spot temperature would not exceed the insulation temperature class.

Table A.4—Continuous per unit loading capability as a function of ambient temperature

Cooling mode	Maximum ambient temperature (°C)	Insulation Temperature class (°C)		
		130	**150**	**180**
AA	10	1.20	1.16	1.12
	20	1.13	1.11	1.08
	30	1.07	1.06	1.04
	40	1.00	1.00	1.00
FA	10	1.15	1.13	1.10
	20	1.11	1.09	1.07
	30	1.05	1.04	1.03
	40	1.00	1.00	1.00

A.8.5.2 Rated temperature loading and loading above rating

Permissible loads and times to reach the limiting hottest-spot temperatures for different values of time constants are given in Table A.5 and Table A.6 for rated temperature loading and loading above rating. A prior load of 70% was used for the calculations. The computer program shown in A.8.7 may be used for other values of prior load and time constant. For some values of time constants, times per unit loads greater than two times rated may be calculated using the equations. This loading guide limits loading to two times nameplate for durations of 1/2 h or greater. This limitation has been incorporated into the computer program and tables. For loads above two times rated kilovolt-ampere output for 30 min or less, see A.9.

A.8.6 Method of converting actual load cycle to equivalent constant load

Permissible loading is a function of the initial load, the peak load, and their durations. Each loading combination may be considered as a simple rectangular load cycle consisting of an essentially constant initial load followed by a rectangular peak of the magnitude and time given in the tables, with the load returning to the initial load at the end of the rectangular peak. The assumed loading for the calculations in the tables is illustrated in Figure A.1.

Table A.5—Short time per unit load capability, rated temperature loading, ambient 30 °C, prior load 70%

Time constant (min)	Time duration (min)	Per unit load for insulation class (°C)		
		130	**150**	**180**
30	15	1.52	1.49	1.47
	30	1.25	1.23	1.21
	60	1.12	1.10	1.09
	90	1.09	1.07	1.06
	150	1.07	1.06	1.04
45	15	1.77	1.74	1.70
	30	1.39	1.37	1.34
	45	1.25	1.23	1.21
	60	1.18	1.17	1.15
	90	1.12	1.10	1.09
60	15	2.00	1.96	1.92
	30	1.52	1.49	1.47
	45	1.34	1.32	1.30
	60	1.25	1.21	1.18
	90	1.16	1.15	1.13
	150	1.10	1.08	1.07
75	15	2.00[a]	2.00[a]	2.00[a]
	30	1.65	1.62	1.59
	45	1.43	1.41	1.38
	60	1.32	1.30	1.28
	90	1.20	1.19	1.17
	150	1.12	1.10	1.09
	180	1.10	1.09	1.07
90	15	2.00[a]	2.00[a]	2.00[a]
	30	1.77	1.74	1.70
	45	1.52	1.49	1.47
	60	1.39	1.37	1.34
	90	1.25	1.23	1.21
	120	1.18	1.17	1.15
	150	1.15	1.13	1.11
	180	1.12	1.10	1.09
120	15	2.00[a]	2.00[a]	2.00[a]
	30	2.00	1.96	1.92
	45	1.69	1.66	1.63
	60	1.52	1.49	1.47
	90	1.34	1.32	1.30
	120	1.25	1.23	1.21
	150	1.20	1.18	1.16
	180	1.16	1.15	1.13

Table A.5—Short time per unit load capability, rated temperature loading, ambient 30 °C, prior load 70% *(continued)*

Time constant (min)	Time duration (min)	Per unit load for insulation class (°C)		
		130	150	180
150	15–30	2.00[a]	2.00[a]	2.00[a]
	45	1.85	1.81	1.78
	60	1.65	1.62	1.59
	90	1.43	1.41	1.38
	120	1.32	1.30	1.28
	150	1.25	1.23	1.21
	180	1.20	1.19	1.17
	240	1.15	1.15	1.13
180	15–30	2.00[a]	2.00[a]	2.00[a]
	45	2.00	1.96	1.85
	60	1.77	1.74	1.65
	90	1.52	1.49	1.43
	120	1.39	1.37	1.31
	150	1.30	1.29	1.24
	180	1.25	1.23	1.19
	240	1.18	1.17	1.13

[a] Calculated load higher than two times normal.

Table A.6—Short time per unit load capability, loading above rating, maximum hottest-spot temperatures per Table 1, ambient 30 °C, prior load 70%

Time constant (min)	Time duration (min)	Per unit load for insulation class (°C)		
		130	150	180
30	15	1.96	1.86	1.75
	30	1.56	1.49	1.42
	60	1.37	1.31	1.25
	90	1.31	1.26	1.21
	150	1.29	1.24	1.19
45	15	2.00[a]	2.00[a]	2.00[a]
	30	1.77	1.68	1.59
	45	1.56	1.49	1.42
	60	1.46	1.40	1.33
	90	1.37	1.31	1.25
60	15	2.00[a]	2.00[a]	2.00[a]
	30	1.96	1.86	1.76
	45	1.70	1.62	1.53
	60	1.56	1.49	1.42
	90	1.43	1.37	1.30
	150	1.33	1.28	1.22

Table A.6—Short time per unit load capability, loading above rating, maximum hottest-spot temperatures per Table 1, ambient 30 °C, prior load 70% *(continued)*

Time constant (min)	**Time duration (min)**	**Per unit load for insulation class (°C)**		
		130	**150**	**180**
75	15	2.00[a]	2.00[a]	2.00[a]
	30	2.00[a]	2.00[a]	1.91
	45	1.83	1.74	1.64
	60	1.67	1.59	1.50
	90	1.49	1.43	1.36
	150	1.37	1.31	1.25
	180	1.33	1.28	1.23
90	15–30	2.00[a]	2.00	2.00[a]
	45	1.96	1.86	1.75
	60	1.77	1.68	1.59
	90	1.56	1.49	1.42
	120	1.46	1.40	1.33
	150	1.40	1.34	1.28
	180	1.37	1.31	1.25
120	15–30	2.00[a]	2.00[a]	2.00[a]
	45	2.00[a]	2.00[a]	1.97
	60	1.96	1.86	1.75
	90	1.70	1.62	1.53
	120	1.56	1.49	1.42
	150	1.48	1.42	1.35
	180	1.43	1.37	1.30
150	15–45	2.00[a]	2.00[a]	2.00[a]
	60	2.00[a]	2.00[a]	1.91
	90	1.83	1.74	1.64
	120	1.67	1.59	1.50
	150	1.56	1.49	1.42
	180	1.49	1.43	1.36
	240	1.41	1.35	1.29
180	15–60	2.00[a]	2.00[a]	2.00[a]
	90	1.96	1.86	1.75
	120	1.77	1.68	1.59
	150	1.65	1.57	1.49
	180	1.56	1.49	1.42
	240	1.46	1.40	1.33

[a] Calculated load higher than two times normal.

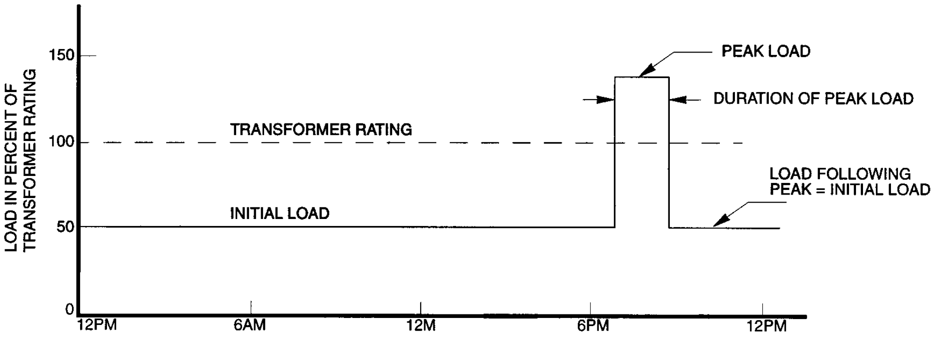

Figure A.1—Assumed load cycle

The daily load cycle more often is like the cycle represented by the solid line in Figure A.2 throughout the day, and usually with one period in the daily load cycle when the load builds up to a considerably greater value than any reached at other times. Generally, the maximum value or peak load is not reached and passed suddenly, but builds up and falls off gradually. To use the loading recommendations, the actual fluctuating load cycle must be converted to a thermally equivalent, simple rectangular load cycle, such as represented by the dashed line in Figure A.2. A transformer supplying a fluctuating load generates a fluctuating loss, the effect of which is about the same as that of an intermediate load held constant for the same period of time. This is due to the heat storage characteristics of the materials in the transformer. A load, generating losses at the same rate as the average rate caused by the fluctuating load, is an equivalent load from a temperature standpoint. Equivalent load for any portion of a daily load cycle may be expressed by Equation (A.13).

$$L_{EQ} = \left[\frac{(L_1^2 t_1 + L_2^2 t_2 + \ldots + L_n^2 t_n)}{(t_1 + t_2 + \ldots + t_n)}\right]^{0.5} \tag{A.13}$$

where

$L_1, L_2, \ldots, L_n$ are the various load steps in percent, per unit, or in actual kilovolt-amperes,

$t_1, t_2, \ldots, t_n$ are the duration of the loads, respectively.

Equivalent initial load is the root-mean-square (rms) load obtained by Equation (A.13) over a chosen period preceding the peak load. Experience with this method of load studies indicates that quite satisfactory results are obtained by considering the 12 h period preceding the peak in the determination of the equivalent initial load. With a time interval of 1 h suggested as a further simplification, the equation for a 12 h period becomes the following:

$$\text{equivalent initial load} = 0.29(L_1^2 + L_2^2 + \ldots + L_{12}^2)^{0.5} \tag{A.14}$$

where

$L_1, L_2, \ldots, L_{12}$ are the average load by inspection for each 1 h interval of the 12 h period preceding peak load.

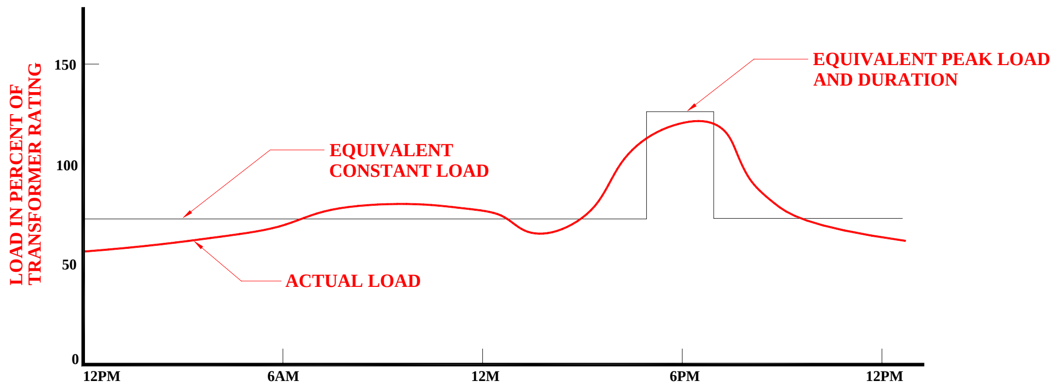

Figure A.2—Actual load cycle

Equivalent peak load for the usual load cycle is the rms load obtained by Equation (A.13) for the limited period over which the major part of the actual irregular peak seems to exist. The estimated duration of the peak has considerable influence over the rms peak value. If the duration is overestimated, the rms peak value may be considerably below the maximum peak demand. To guard against overheating due to high, brief overloads during the peak period, the rms value for the peak load should not be less than 90% of the integrated 1/2 h maximum demand.

A.8.7 Computer program

The computer program using BASIC language developed to calculate data for Table A.4, Table A.5, and Table A.6 is shown below.

```
10 REM PROGRAM CLOAD

20 REM CALCULATES LOAD CAPABILITY

30 REM CAST RESIN TRANSFORMERS

40 REM L1 = PRIOR PER UNIT LOAD

50 REM T1 = AMBIENT TEMPERATURE

60 REM T2 = RATED HOT SPOT RISE

70 REM T6 = MAXIMUM LIMITING HS TEMP

80 REM T9 = WINDING TIME CONSTANT, MIN.

90 REM BOTH HV AND LV SHOULD BE

100 REM CHECKED, TIME CONSTANTS DIF.

110 READ L1,T1,T2,T6,T9

120 REM T3 = INITIAL HOT SPOT RISE

130 REM T4 = MAXIMUM LIMITING HS RISE
```

```
140 REM T5 = ULTIMATE HOT SPOT RISE

150 REM N = EXPONENT FOR HEATING

160 REM L2 = SHORT-TIME LOAD CAPABILITY

170 REM DEPENDS ON SELECTION

180 REM OF MAXIMUM LIMITING HS

190 REM TEMPERATURE, T6

200 OPEN "CLCAP.TXT" FOR OUTPUT AS #1

210 PRINT #1,"PRIOR LOAD = ",L1

220 PRINT #1,"AMBIENT TEMPERATURE = ",T1

230 PRINT #1, "RATED HOT SPOT RISE = ",T2

240 PRINT #1,"MAX. LIMITING HS TEMP = ",T6

250 PRINT #1,"TIME CONSTANT, MINUTES = ",T9

260 T4 = T6 - T1

270 N = .8

280 T3 = T2*(L1^(2*N))

290 T3 = T2*(L1^1.6)

300 PRINT #1,"SHORT-TIME LOAD CAPABILITY, SELF-COOLED"

310 PRINT #1,"     ","TIME, MIN.","LOAD, PU"

320 FOR T8 = 15 TO 240 STEP 15

330 X = 1 - EXP(-T8/T9)

340 T5 = ((T4 - T3)/X) + T3

350 X2 = 1/(2*N)

360 L2 = (T5/T2)^X2

370 IF L2>2 THEN L2 = 2

380 PRINT #1,"     ",T8,L2

390 NEXT T8

400 DATA .70,30,90,130,180

410 END
```

Example program output used for Table A.5

```
PRIOR LOAD = .7

AMBIENT TEMPERATURE = 30

RATED HOT SPOT RISE = 90

MAX. LIMITING HS TEMP   = 130

TIME CONSTANT, MINUTES = 180

SHORT-TIME LOAD CAPABILITY, SELF-COOLED

      TIME, MIN   LOAD, PU

       15          2

       30          2

       45          2

       60          1.769101

       75          1.621648

       90          1.519323

      105          1.444161

      120          1.386684

      135          1.341396

      150          1.304876

      165          1.274882

      180          1.249877

      195          1.228774

      210          1.21078

      225          1.195303

      240          1.18189
```

A.9 High frequency of operation loading

Cast-resin transformers are especially suitable for short-time loads above rating that occur frequently, such as motor starting or impact type loading. An application curve for pulsating or short-time loads is given in Figure A.3. This curve, based on application experience with other transformer types, is thought to represent conservative loading practice for cast-resin transformers. Figure A.3 covers the range of application between those described as short circuit faults given in IEEE Std C57.12.59-1989 and longer duration overloads described in A.8.

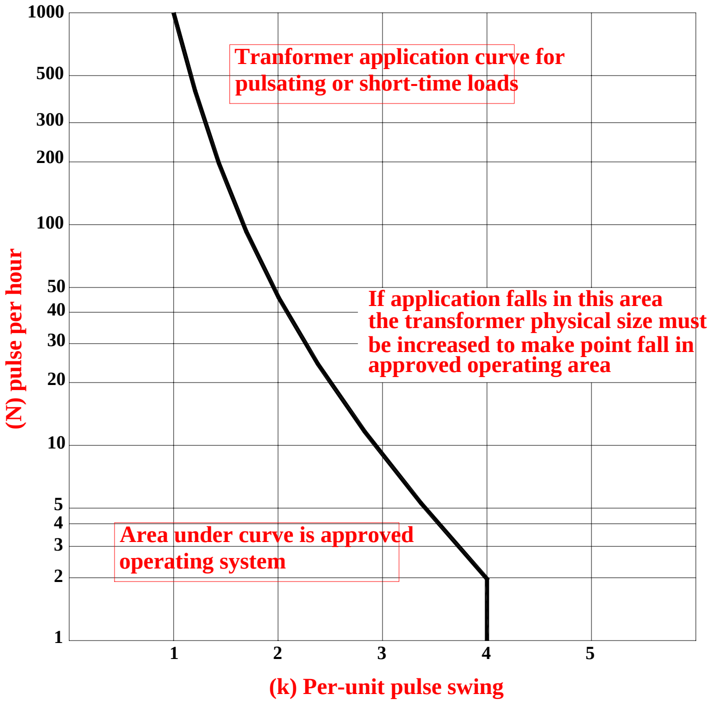

Figure A.3—Application curve for pulsating or short-time loads

A.10 Fan cooling

The addition of fans increases the load capability for peak loading during the load cycle or during emergency loading. Increased load capability with fans varies with the manufacturer. Designing cast-resin transformers to required hottest-spot temperature limits becomes increasingly difficult as the fan-cooled rating increases.

A.11 Test reports

It is recommended that specifications require that the following information be included on transformer test reports:

a) Hottest-spot temperature rise of high-voltage winding;

b) Average temperature rise of high-voltage winding;

c) Time constant of high-voltage winding;

d) Hottest-spot temperature rise of low-voltage winding;

e) Average temperature rise of low-voltage winding;

f) Time constant of low-voltage winding.

Annex B

(informative)

Bibliography

[B1] den Outer, F. R., “The Loading of Solid-Insulation Distribution Transformers with Special Reference to the Cast Resin Type,” *Proc. International Conference on Electricity Distribution (CIRED 1977),* London, 23–27 May 1977. Part I, pp. 75–79, Discussion Part II, pp. 31–32, 37, 41–42.

[B2] Featheringill, W. E., “Power Transformer Loading,” *IEEE Transaction on Industry Applications,* vol. IA-19, no. 1, pp. 21–27, Jan./Feb. 1983.

[B3] IEC 60905: 1987, Loading Guide for Dry-Type Power Transformers.

[B4] Pierce, L. W., “An Investigation of the Temperature Distribution in Cast-Resin Transformer Windings,” *IEEE Transactions on Power Delivery,* vol. 7, no. 1, pp. 920–926, Apr. 1992.

[B5] Ristow, R. J., and McCann, F. J., “Problems of Impact Loading on Unit Transformers Supplying Chipper Motor Drives,” *Proceedings Sixteenth Annual IEEE Pulp and Paper Conference,* June 1970.

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