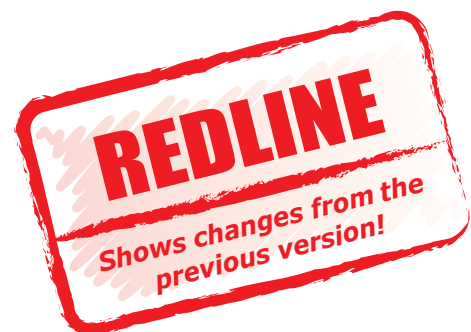


IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators

IEEE Power & Energy Society

Sponsored by the
Transformers Committee



IEEE
3 Park Avenue
New York, NY 10016-5997
USA

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IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators

Sponsor

Transformers Committee
of the
IEEE Power & Energy Society

Approved 7 December 2011

IEEE-SA Standards Board

Abstract: General recommendations for loading 65 °C rise mineral-oil-immersed distribution and power transformers are covered.

Keywords: distribution transformer, IEEE C57.91, loading, mineral-oil-immersed, power transformer

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Introduction

This introduction is not part of IEEE Std C57.91-2011, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators.

This guide is applicable to loading 65 °C mineral-oil-immersed distribution and power transformers. Guides for loading, IEEE Std C57.91-1981 (prior edition), IEEE Std C57.92™-1981,^a and IEEE Std C57.115-1991 (redesignated as IEEE Std 756) are all combined in this document as the basic theory of transformer loading is the same, whether the subject is distribution transformers, power transformers 100 MVA and smaller, or transformers larger than 100 MVA. In recognition of different types of construction, special considerations, and the degree of conservatism involved in the loading of this equipment, specific sections are devoted to power transformers and distribution transformers. In the previously referenced information, the guide for units larger than 100 MVA referenced the IEEE Std C57.92-1981 loading guide for units up to and including 100 MVA.

This update to the work done in 1995 expands the scope to include step-voltage regulators and replaces Annex A with an improved discussion on bubble evolution. Subclause 8.4 was added for step-voltage regulators. In addition, the formula notations were changed to reflect the updated IEEE style and a number of typographical errors were fixed. Both Clause 7 and Annex G calculation procedures remain in place. Clause J was removed as out-of-date information and is expected to be re-introduced in the future in a new standard on transformer monitoring systems. Annex C and Annex G were changed from normative to informative.

As IEEE Std C57.12.00-2010^b has adopted an insulation life of 180 000 hours at 110 °C, Table 2 of this guide has been moved to Annex I for historical reference.

In previous guides, different insulation aging curves were used for power transformers and distribution transformers. This was caused by the different evaluation procedures used. The distribution transformer curve was based on aging tests of actual transformers. The power transformer curve was based on aging insulation samples in test containers to achieve 50% retention of tensile strength. Investigation of cellulosic insulating materials removed from transformers that had long service life has led knowledgeable people to question the validity of the 50% criteria. One newer criteria suggested is 25% retention. This guide will permit the user to select the criteria most acceptable to their need, based on percent strength retention, polymerization index, etc. An insulation aging factor may thus be applied.

A per unit life concept and aging acceleration factor are provided in this loading guide. The equations given may be used to calculate percent loss of total insulation life, as has been the practice in earlier editions of the transformer loading guides. The relationship between insulation life and transformer life is a question that remains to be resolved. It is recognized that under the proper conditions, transformer life can well exceed the life of the insulation.

The assumed characteristics used in previous guides contained tables of loading capability based on assumed typical transformer characteristics. These assumed characteristics were recognized as not being those of actually built units, which may have a wide range of characteristics. In this guide these tables were removed since computer technology permits calculation of loading capability based on specific transformer characteristics.

Two methods of calculating temperatures are given in this guide. Clause 7 contains temperature equations similar to those used in previous editions of this guide. These equations use the winding hot spot rise over tank top oil and assume that the oil temperature in the cooling ducts is the same as the tank top oil during overloads. Recent research using imbedded thermocouples and fiber optic detectors indicates that the fluid

^a IEEE Std C57.92-1981 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/>).

^b Information of references can be found in Clause 2.

flow occurring in the windings during transient heating and cooling is an extremely complicated phenomena to describe by simple equations. These recent investigations have shown that during overloads, the temperature of the oil in the winding cooling ducts rises rapidly and exceeds the top-oil temperature in the tank. An alternate set of equations based on this concept is given in Annex G. The change of losses with temperature and liquid viscosity effects, and variable ambient temperature was incorporated into the equations. A computer program based on these equations is given for evaluation by the industry. Research in this field is ongoing at this time and may be incorporated into future revisions of this guide.

Changes in the guide, in addition to the consolidation, include information to more accurately load transformers operating down to a $-30\text{ }^{\circ}\text{C}$ ambient, this information concerns loss of diversity due to cold load pick-up or unusually low ambient temperatures.

Transformers rated $55\text{ }^{\circ}\text{C}$ rise were generally replaced as a standard offering by most manufacturers about 1966. Their replacements were originally rated $55/65\text{ }^{\circ}\text{C}$ and in 1977 the single $65\text{ }^{\circ}\text{C}$ rated transformers became the industry standard offering. The higher temperature ratings are based on thermally upgraded oil-paper-enamel insulation systems. Loading of $55\text{ }^{\circ}\text{C}$ insulation system transformers is covered in Annex D.

Suggestions for improvement gained in the use of this guide will be welcomed. They should be sent to the IEEE Standards Department.

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1. Overview

1.1 Scope

This guide provides recommendations for loading mineral-oil-immersed transformers and step-voltage regulators with insulation systems rated for a 65 °C average winding temperature rise at rated load. This guide applies to transformers ~~are included~~ manufactured in accordance with IEEE Std C57.12.00¹ and tested in accordance with IEEE Std C57.12.90, and step-voltage regulators manufactured and tested in ~~annex D~~ because accordance with IEEE Std C57.15. Because a substantial ~~percentage population~~ of these transformers and step-voltage regulators with insulation systems rated for 55 °C average winding temperature rise at rated load are still in service, recommendations that are specific to this equipment are also included.

1.2 Purpose

Applications of loads in excess of nameplate rating involve some degree of risk. It is the purpose of this guide to identify these risks and to establish limitations and guidelines, the application of which will minimize the risks to an acceptable level.

¹Information of references can be found in Clause 2.

~~Risk areas are identified in clauses 4 and 9, and in the annexes as noted.~~

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 should be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision should apply.~~

~~ANSI C57.12.10-1988, American National Standard for Transformers 230 kV and Below, 833/958 through 8333/10 417 kVA Single Phase, and 750/862 through 60 000/80 000/100 000 kVA Three Phase, without~~

~~Load Tap Changing; and 3750/4687 through 60 000/80 000/100 000 kVA with Load Tap Changing Requirements.[†]~~

~~ANSI C57.12.20-1988, Requirements for Overhead Type Distribution Transformers, 500 kVA and Smaller: High Voltage, 34 500 Volts and Below; Low Voltage, 7970/13 800Y and Below.~~

[†]~~ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.~~

~~ANSI C57.12.21-1980, Requirements for Pad Mounted, Compartmental Type, Self-Cooled, Single Phase Distribution Transformers with High Voltage Bushings (High Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 240/120 Volts; 167 kVA and Smaller).~~

~~ANSI C57.12.22-1989, Pad Mounted, Compartmental Type, Self-Cooled, Three Phase Distribution Transformers with High Voltage Bushings, 2500 kVA and Smaller: High Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 480 Volts and Below—Requirements.~~

~~ANSI C57.12.25-1990, Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with Separable-Insulated High-Voltage Connectors: High-Voltage, 34-500 GrdY/19 920 Volts and Below; Low-Voltage 240/120 Volts; 167 kVA and Smaller.~~

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.^{2,3}

~~IEEE Std C57.12.26-1992, IEEE Standard for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable-Insulated High-Voltage Connectors (34-500 Grd Y/19 920 V and Below; 2500 kVA and Smaller) (ANSI).~~

IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.15™, IEEE Standard [Requirements, Terminology, and Test Code for Step-Voltage Regulators](#).

[IEEE Std C57.100™, IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-Immersed Distribution and Power Transformers](#).

3. Definitions

[For the purposes of this document, the following terms and definitions apply. The IEEE Standards Dictionary: Glossary of Terms and Definitions⁴ should be consulted for terms not defined in this clause.](#)

aging acceleration factor: For a given hottest-spot temperature, the rate at which transformer insulation aging is accelerated compared with the aging rate at a reference hottest-spot temperature. The reference hottest-spot temperature is 110 °C for 65 °C average winding rise and 95 °C for 55 °C average winding rise transformers (without thermally upgraded insulation). For hottest-spot temperatures in excess of the reference hottest-spot temperature, the aging acceleration factor is greater than 1. For hottest-spot temperatures lower than the reference hottest-spot temperature, the aging acceleration factor is less than 1.

directed flow (oil-immersed forced-oil-cooled transformers): The principal part of the pumped [insulating fluid](#) from heat exchangers or radiators is forced, [or directed](#), to flow through [specific paths](#) in the winding.

non-directed flow (oil-immersed forced-oil-cooled transformers): Indicates that the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings.

percent loss of life: The equivalent aging in hours at the reference hottest-spot temperature over a time period (usually 24 h) times 100 divided by the total normal insulation life in hours at the reference hottest-spot temperature. The equivalent aging in hours at different hot-spot temperatures is obtained by multiplying the aging acceleration factors for the hottest-spot temperatures times the time periods of the various hottest-spot temperatures.

transformer insulation life: For a given temperature of the transformer insulation, the total time between the initial state for which the insulation is considered new and the final state for which dielectric stress, short circuit stress, or mechanical movement, which could occur in normal service, and could cause an electrical failure.

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4. Effect of loading beyond nameplate rating

4.1 General

Applications of loads in excess of nameplate rating involve some degree of risk. While aging and long time mechanical deterioration of winding insulation have been the basis for the loading of transformers for many years, it is recognized that there are additional factors that may involve greater risk for transformers of higher megavoltampere and voltage ratings. The risk areas that should be considered when loading large transformers beyond nameplate rating are listed next. Further discussion regarding these risks is provided in Clause 9 or in the annexes, as noted.

- a) Evolution of free gas from insulation of winding and lead conductors (insulated conductors) heated by load and eddy currents (circulating currents between or within insulated conductor strands) may jeopardize dielectric integrity. See Annex A for further discussion.
- b) Evolution of free gas from insulation [and insulating fluid](#) adjacent to metallic structural parts linked by electromagnetic flux produced by winding or lead currents may also reduce dielectric strength.
- c) Loss of life calculations may be made as described in Clause 5. If a percent loss of total life calculation is made based on an arbitrary definition of a “normal life” in hours, one should recognize that the calculated results may not be as conservative for transformers rated above 100 MVA as they are for smaller units since the calculation does not consider mechanical wear effects that may increase with megavoltampere rating.
- d) Operation at high temperature will cause reduced mechanical strength of both conductor and structural insulation. These effects are of major concern during periods of transient overcurrent (through-fault) when mechanical forces reach their highest levels.
- e) Thermal expansion of conductors, insulation materials, or structural parts at high temperatures may result in permanent deformations that could contribute to mechanical or dielectric failures.
- f) Pressure build-up in bushings for currents above rating could result in leaking gaskets, loss of oil, and ultimate dielectric failure. See Annex B for further discussion.
- g) Increased resistance in the contacts of tap changers can result from a build-up of oil decomposition products in a very localized high temperature region at the contact point when the tap changer is loaded beyond its rating. In the extreme, this could result in a thermal runaway condition with contact arcing and violent gas evolution. See Annex B for further discussion.
- h) Auxiliary equipment internal to the transformer, such as reactors and current transformers, may also be subject to some of the risk identified above. See Annex B for further discussion.
- i) When the temperature of the top oil exceeds 105 °C (65 °C rise over 40 °C ambient according to IEEE Std C57.12.00), there is a possibility that oil expansion will be greater than the holding capacity of the tank and also result in a pressure that causes the pressure relief device to operate and expel the oil. The loss of oil may also create problems with the oil preservation system or expose electrical parts upon cooling.

4.2 Voltage and frequency considerations

Voltage and frequency influences should be recognized when determining limitations for loading a transformer beyond its nameplate rating. This is true even though in all probability there may be little control of these parameters during a loading beyond nameplate rating event. ~~Subclause 4.1.6 in~~ IEEE Std C57.12.00-1993 defines the capability of a transformer to operate above rated voltage and below rated frequency. The user of this guide should recognize that, during conditions of loading beyond nameplate, the voltage regulation through the transformer may increase significantly (depending on the transformer impedance) due to the increased kilovoltampere loading and possibly dropping power factor.

A conservative guideline to prevent excessive core heating due to increased excitation is to reduce the transformer output volts per hertz limit by 1% for every 1% increase in voltage regulation during the loading beyond nameplate event. For example, if the voltage regulation at rated conditions is 6% and increases to 9% at some load above nameplate, the output volts per hertz limit might be reduced from 105% to 102%.

4.3 Supplemental cooling of existing self-cooled transformers

The load that can be carried on existing self-cooled transformers can usually be increased by adding auxiliary cooling equipment such as fans, external forced-oil coolers, or water spray equipment. The amount of additional loading varies widely, depending upon the following:

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

No general rules can be given for such supplemental cooling, and each transformer should be considered individually.

The use of water spray equipment for supplemental cooling is not recommended for use in normal loading beyond nameplate rating. Appropriate precautions should be made for application of water spray equipment for supplemental cooling during emergency overloads. The major problem is the build up of scale on the cooling equipment due to minerals in the water. Over the long term this buildup will hinder the cooling efficiency. The spray and steam generated can also cause phase-to-phase flashover between bushings.

4.4 Information for user calculations

If the user intends to perform calculations to determine the loading capability of a transformer using Clause 7 or Annex G, the user should request the following minimum information in the specification or final test report:

- a) Top-oil temperature rise over ambient temperature at rated load
- b) Bottom-oil temperature rise over ambient temperature at rated load
- c) Average conductor temperature rise over ambient temperature at rated load
- d) Winding hottest-spot temperature rise over ambient temperature at rated load
- e) Load loss at rated load
- f) No-load (core) loss
- g) Total loss at rated load
- h) Confirmation of oil flow design (that is, directed or non-directed)
- i) Weight of core and coil assembly
- j) Weight of tank and fittings

NOTE —For the purpose of transient thermal calculations, the weight of tank and fittings to be used are only those portions that are in contact with heated oil.⁵

- k) Volume of oil in the tank and cooling equipment (excluding LTC compartments, oil expansion tanks, etc.)

⁵ [Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.](#)

For all of the information in a) through g), the conditions under which the measurements were made (load, ambient temperature, tap, etc.) should be stated. If test data from thermally similar units is supplied the data shown on the test report should be corrected (in accordance with IEEE recommended procedures when issued) by the manufacturer using the actual design characteristics (losses, cooling surface, etc.) of the transformer supplied.

More precise calculations of loading capability may be performed if desired using Clause 7 or Annex G if the following additional information is provided:

- Load loss at rated load at rated and tap extremes or all possible tap connection combinations
- Winding resistance at tap extremes or all possible tap combinations

More precise calculations of loading capability may be performed if desired using Annex G if the following additional information is also provided:

- Total stray and eddy loss as a percent of total load loss and estimated stray and eddy loss
- Per unit eddy loss at hot spot location
- Per unit winding height to hot spot location

The temperature rise test is performed (and calculations of temperature rises made when a test is not performed) on the maximum loss tap position. This data results in conservative predictions of loading capability when the transformer is operated on other than the maximum loss tap. To achieve more accurate predictions of the capability of a transformer based on the actual loading cycle and tap connections, several adjustments may be made of the data presented in the test report before the data is used as input to loading calculations. These adjustments are provided in the following:

- Load cycle in kVA on the actual combination of tap connections-
- Use the measured or calculated load losses for that tap connection-
- Correct the temperature rise test data for the lower losses or different rated current-
- Determine if the hottest-spot winding gradient changes with changes in the tap connections-

Calculating the effect of load tap changer operation into the loading predictions is an extremely complicated and controversial subject and the effect may vary with manufacturer. For some designs the effect of load tap changer operation may have a negligible effect on temperature rises of the transformer windings.

5. Transformer insulation life

5.1 General

The subject of loss of transformer insulation life has had a rich but controversial history of development, with distribution and power transformers taking independent research paths (refer to I.1 in Annex I). As a result of recent study and testing, the approach to determination of insulation loss of life in this guide has been significantly modified (refer to I.2 in Annex I.) Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. With modern oil preservation systems, the moisture and oxygen contributions to insulation deterioration can be minimized, leaving insulation temperature as the controlling parameter. Since, in most apparatus, the temperature distribution is not uniform, the part that is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, in aging studies it is usual to consider the aging effects produced by the highest (hottest-spot) temperature. Because many factors influence the cumulative effect of temperature over time in causing deterioration of transformer insulation, it is not possible to predict with any great degree of accuracy the useful life of the insulation in a transformer, even under constant or closely controlled conditions, much less under widely varying service conditions. Wherever the word “life” is used in this guide, it means calculated insulation life, not actual transformer life.

5.2 Aging equations

Experimental evidence indicates that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory that has the following form:

$$\text{Per Unit Life} = A e^{\left[\frac{B}{\Theta_H + 273} \right]}$$

where

Θ_H is the winding hottest-spot temperature, °C

A is a constant

B is a constant

e is the base of the natural logarithm

The transformer per unit insulation life curve of Figure 1 relates per unit transformer insulation life to winding hottest-spot temperature. This curve should be used for both distribution and power transformers because both are manufactured using the same cellulose conductor insulation. The use of this curve isolates temperature as the principal variable affecting thermal life. It also indicates the degree to which the rate of aging is accelerated beyond normal for temperature above a reference temperature of 110 °C and is reduced below normal for temperature below 110 °C (see discussion in I.2 of Annex I). The equation for the curve is as follows:

$$\text{Per Unit Life} = 9.8 \times 10^{-18} e^{\left[\frac{15000}{\Theta_H + 273} \right]} \quad (1)$$

where

Θ_H is the winding hottest-spot temperature, °C

The per unit transformer insulation life curve (Figure 1) can be used in the following two ways. It is the basis for calculation of an aging acceleration factor (F_{AA}) for a given load and temperature or for a varying load and temperature profile over a 24 h period. A curve of F_{AA} vs. hottest-spot temperature for a 65 °C rise insulation system is shown in Figure 2 and values are tabulated in Table 1. F_{AA} has a value greater than 1 for winding hottest-spot temperatures greater than the reference temperature 110 °C and less than 1 for temperatures below 110 °C. The equation for F_{AA} is as follows:

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\Theta_H + 273} \right]} \quad (2)$$

where

F_{AA} is the aging acceleration factor

Θ_H is the winding hottest-spot temperature, °C

Equation (2) may be used to calculate equivalent aging of the transformer. The equivalent aging factor at the reference temperature ~~that will be consumed~~ in a given time period for the given temperature cycle is the following:

$$F_{EQA} = \frac{\sum_{n=1}^N F_{AA,n} \Delta t_n}{\sum_{n=1}^N \Delta t_n} \quad (3)$$

where

F_{EQA} is equivalent aging factor for the total time period

$F_{AA,n}$ is aging acceleration factor for the temperature that exists during the time interval Δt_n

n is index of the time interval, Δt

N is total number of time intervals

Δt_n is time interval, h

See Annex I for example calculations.

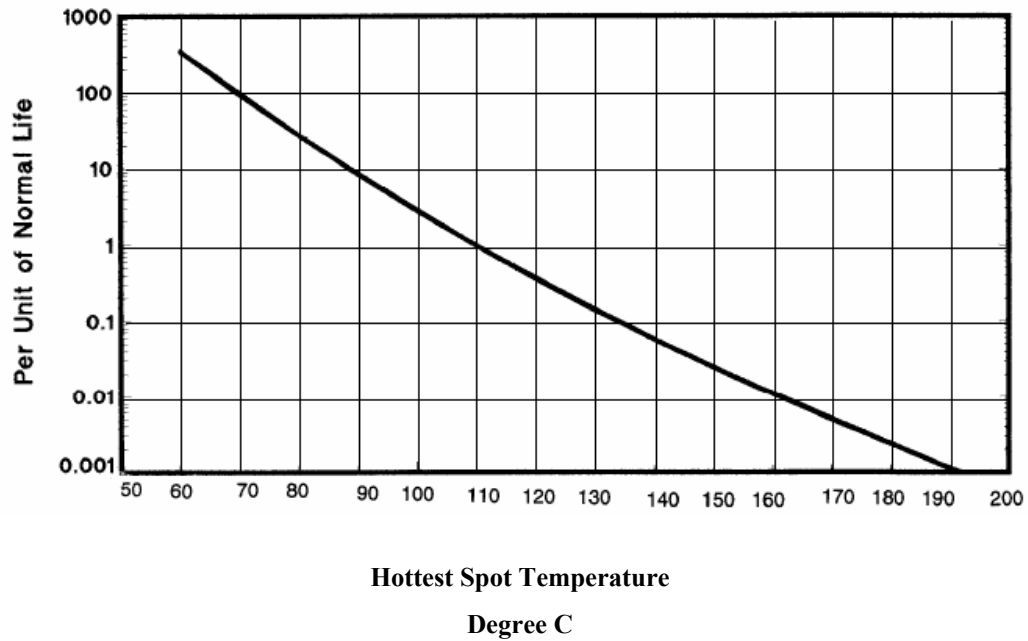


Figure 1 — Transformer insulation life

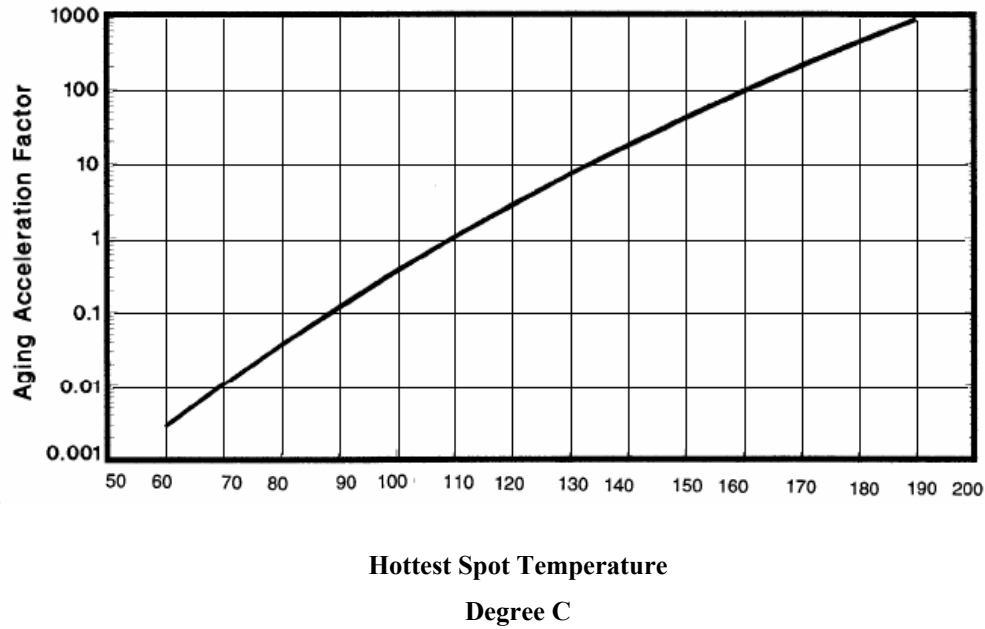


Figure 2 — Aging acceleration factor (relative to 110 °C)

Table 1—Aging acceleration factor

Temperatu re °C	Age factor	Temperatu re °C	Age factor	Temperatu re °C	Age factor
<37	0.0000	91	0.1295	146	28.9315
37	0.0001	92	0.1449	147	31.5115
38	0.0001	93	0.1622	148	34.3015
39	0.0001	94	0.1813	149	37.3215
40	0.0002	95	0.2026	150	40.5915
41	0.0002	96	0.2263	151	44.1315
42	0.0002	97	0.2526	152	47.9615
43	0.0002	98	0.2817	153	52.1015
44	0.0003	99	0.3141	154	56.5815
45	0.0003	100	0.3499	155	61.4215
46	0.0004	101	0.3897	156	66.6516
47	0.0004	102	0.4337	157	72.3016
48	0.0005	103	0.4823	158	78.3916
49	0.0006	104	0.5362	159	84.9716
50	0.0007	105	0.5957	160	92.0616
51	0.0008	106	0.6614	161	99.7116
52	0.0009	107	0.7340	162	107.9616
53	0.0011	108	0.8142	163	116.8416

54	0.0012	109	0.9026	164	126.4116
55	0.0014	110	1.0000	165	136.7216
56	0.0016	111	1.1074	166	147.8117
57	0.0019	112	1.2256	167	159.7517
58	0.0021	113	1.3558	168	172.5817
59	0.0024	114	1.4990	169	186.3917
60	0.0028	115	1.6565	170	201.2317
61	0.0032	116	1.8296	171	217.1817
62	0.0037	117	2.0197	172	234.3017
63	0.0042	118	2.2285	173	252.7017
64	0.0048	119	2.4576	174	272.4517
65	0.0054	120	2.7089	175	293.6417
66	0.0062	121	2.9845	176	316.3718
61	0.0071	122	3.2865	177	340.7518
68	0.0080	123	3.6172	178	366.8918
69	0.0091	124	3.9793	179	394.9118
70	0.0104	125	4.3756	180	424.9218
71	0.0118	126	4.8091	181	457.0718
72	0.0134	127	5.2830	182	491.5018
73	0.0152	128	5.8009	183	528.3518
74	0.0172	129	6.3665	184	567.7818
75	0.0195	130	6.9842	185	609.9618
76	0.0220	131	7.6582	186	655.0819
77	0.0249	132	8.3935	187	703.3119
78	0.0281	133	9.1952	188	754.8619
79	0.0318	134	10.0689	189	809.9419
80	0.0358	135	11.0208	190	868.7719
81	0.0404	136	12.0573	191	931.6019
82	0.0455	137	13.1856	192	998.6719
83	0.0513	138	14.4131	193	1070.2519
84	0.0577	139	15.7481	194	1146.6219
85	0.0649	140	17.1994	195	1228.0819
86	0.0729	141	18.7765	196	1314.9420
87	0.0819	142	20.4895	197	1407.5420
88	0.0919	143	22.3493	198	1506.2220
89	0.1031	144	24.3679	199	1611.3520
90	0.1156	145	26.5578	200	1723.3420

5.3 Percent loss of life

The insulation per unit life curve (see Figure 1) can also be used to calculate percent loss of total life, as has been the practice in earlier editions of the referenced transformer loading guides. To do so, it is necessary to arbitrarily define the normal insulation life at the reference temperature in hours or years. Benchmark values of normal insulation life for a well-dried, oxygen-free system can be selected from Table I.2. Then the hours of life lost in the total time period is determined by multiplying the equivalent aging determined in Equation (3) by the time period (t) in hours. This gives equivalent hours of life at the reference temperature that are consumed in the time period. Percent loss of insulation life in the time period is equivalent hours life consumed divided by the definition of total normal insulation life (h) and multiplied by 100. Usually the total time period used is 24 h. The equation is given as follows:

$$\% \text{ Loss of life} = \frac{F_{EQA} \times t \times 100}{\text{Normal insulation life}} \quad (4)$$

where

F_{EQA} is equivalent aging factor for the total time period

Per 5.11.3 of IEEE Std C57.12.00-2010, a minimum normal insulation life expectancy of 180 000 hours is required. Other values for the end of life criteria have been used historically for developing transformer loading capability studies. The equations provided in this clause include a variable for the end of life criteria, so those users who have used alternative values may continue to do so. The end of life criteria are described in Table I.2 of Annex I.

The time duration for continuous operation at hottest-spot temperatures above rated that give different percent loss of life may be calculated using Equation (4). Table 2 gives time durations for various loss of life based on a normal life of 180 000 h. Normal percent loss of life for operation at a rated hottest-spot temperature of 110 °C for 24 h is 0.0133%.

Table 2—Time durations in hours for continuous operation above rated hottest-spot temperature for different loss of life values

Hot spot temp °C	F _{AA}	Percent loss of life ^a						
		0.0133 ^b	0.02	0.05	0.1	0.2	0.3	0.4
110	1.00	24	—	—	—	—	—	—
120	2.71	8.86	13.3	—	—	—	—	—
130	6.98	3.44	5.1	12.9	—	—	—	—
140	17.2	1.39	2.1	5.2	10.5	20.9	—	—
150	40.6	0.59	0.89	2.2	4.4	8.8	13.3	17.7
160	92.1	0.26	0.39	0.98	1.96	3.9	5.9	7.8
170	201.2	0.12	0.18	0.45	0.89	1.8	2.7	3.6
180	424.9	0.06	0.08	0.21	0.42	0.84	1.27	1.7
190	868.8	0.028	0.04	0.10	0.21	0.41	0.62	0.82
200	1723	0.014	0.02	0.05	0.10	0.21	0.31	0.42

^a Based on a normal life of 180 000 h. Time durations not shown are in excess of 24 h.

^b This column of time durations for 0.0133% loss of life gives the hours of continuous operation above the basis-of-rating hottest-spot temperature (110 °C) for one equivalent day of operation at 110 °C

6. Ambient temperature and its influence on loading

6.1 General

Ambient temperature is an important factor in determining the load capability of a transformer since the temperature rises for any load must be added to the ambient to determine operating temperatures. Transformer ratings are based on a 24 h average ambient of 30 °C. This is the standard ambient used in this guide. Whenever the actual ambient can be measured, such ambients should be averaged over 24 h, and then used in determining the transformer's temperature and loading capability. The ambient air temperature seen by a transformer is the air in contact with its radiators or heat exchangers. In some installations the transformer may be outdoors but surrounded by buildings or sound deadening walls. This may result in recirculation of air, and the ambient should be adjusted accordingly.

6.2 Approximating ambient temperature for air-cooled transformers

It is often necessary to predict the load that a transformer can safely carry at some future time in an unknown ambient. The probable ambient temperature for any month may be approximated from data in reports prepared by the national or local atmospheric authority for the sections of the country where the transformer is located.

- a) *Average temperature*. Use average daily temperature for the month involved, averaged over several years.
- b) *Maximum daily temperature*. Use average of the maximum daily temperatures for month involved averaged over several years.

These ambients should be used as follows:

- For loads with normal life expectancy, use a), the average temperature as the ambient for the month involved.
- [For short-time loads with moderate sacrifice of life expectancy, use b\), the maximum daily temperature for the month involved.](#)

During any one day the 24 h average of temperature may exceed the value derived from a) or b) above. To be conservative it is recommended that these temperatures be increased by 5 °C since aging at higher than average temperature is not fully compensated by decreased aging at lower than average temperature. With this margin the approximated 24 h average temperature will not be exceeded on more than a few days per month and, where it is exceeded, the additional loss of life will not be serious.

6.3 Approximating ambient temperature for water-cooled transformers

The ambient temperature to be used for water-cooled transformers is the cooling water temperature plus an added 5 °C to allow for possible loss of cooling efficiency due to deposits on cooling coil surfaces of water-cooled transformers in service.

6.4 Influence of ambient on loading for normal life expectancy

Average ambient temperatures should cover 24 h time periods. The associated maximum temperatures should not be more than 10 °C above the average temperatures for air-cooled, and 5 °C for water-cooled transformers. Since 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 should always be considered in outdoor installations.

Table 3 gives the increase or decrease from rated kVA for other than average daily ambients of 30 °C for air and 25 °C for water. It is recommended that a 5 °C margin be used when applying the factors from Table 3. It should be pointed out that the increase or decrease obtained from Table 3 is conservative, and therefore do not check exactly with calculations using the equations in Clause 7. Table 3 is for quick approximations, only. Loading on the basis of ambient temperature with loads permitted in Table 3 will give approximately the same life expectancy as if transformers were operated at nameplate rating and standard ambient temperatures over the same period. Table 3 covers a range in average ambient temperatures of –30 °C to 50 °C for cooling air. A check should be made with the manufacturer before loading on the basis of ambient air less than –30 °C or greater than 50 °C.

Table 3—Loading on basis of temperatures (average ambient other than 30 °C and average winding rise less than limiting values) (for quick approximation) (ambient temperature range –30 °C to 50 °C)

Type of cooling	% of kVA rating	
	Decrease load for each °C higher temperature	Increase load for each °C lower temperature
Self-cooled—ONAN	1.5	1.0
Water-cooled—ONWF	1.5	1.0
Forced-air-cooled—ONAN/ONAF, ONAN/ONAF/ONAF	1.0	0.75
Forced-oil, -air, -water-cooled—OFAF, OFWF, ODWF, and ONAN/OFAF/OFAF	1.0	0.75

7. Calculation of temperatures

7.1 Load cycles

7.1.1 Load cycles, general

Transformers usually operate on a load cycle that repeats every 24 h. A typical normal load cycle, such as shown in Figure C.1 of Annex C, consists of load fluctuations throughout the day. For normal loading or planned overloading above nameplate, a multi-step load cycle calculation method is usually used. The 24 h load profile is described by a series of constant loads of a short duration (usually 1/2 h or 1 h). The equivalent load during the short time steps may be determined by the method of 7.1.2 or by using the maximum peak load during the short-time period under consideration. This method is usually used in computer programs.

An equivalent two step overload cycle as shown in Figure 3 may be used for determining emergency overload capability using the Equation (5) through Equation (22). The equivalent two-step load cycle consists of a prior load and a peak load. This figure is also used for the purpose of describing calculations to determine equivalent load cycles. There is usually one period in the daily load cycle when the load builds up to a considerably greater value than any reached at other times, such as shown by the solid line in the overload cycle in Figure 3. Generally, the maximum value or peak load is not reached and passed suddenly, but builds up and falls off gradually. Calculations using the multi-step load cycle described in the previous paragraph may also be performed for emergency overload cycles if desired.

7.1.2 Method of converting actual to equivalent load cycle

A transformer supplying a fluctuating load generates a fluctuating loss, the effect of which is about the same as that of an intermediate constant load for the same period of time. This is due to the heat storage characteristics of the materials in the transformer. A constant load that generates the same total losses as a fluctuating load is assumed an equivalent load from a temperature standpoint. Equivalent load for any part of a daily load cycle may be expressed by Equation (5).

$$\left[\frac{L_1^2 t_1 + L_2^2 t_2 + L_3^2 t_3 + \dots + L_N^2 t_N}{t_1 + t_2 + t_3 + \dots + t_N} \right]^{0.5} \quad (5)$$

where

$L_1, L_2, \dots$ is various load steps in %, per unit, or in actual kVA or current

N is the total number of loads considered

$t_1, t_2, \dots$ is the respective durations of these loads, h

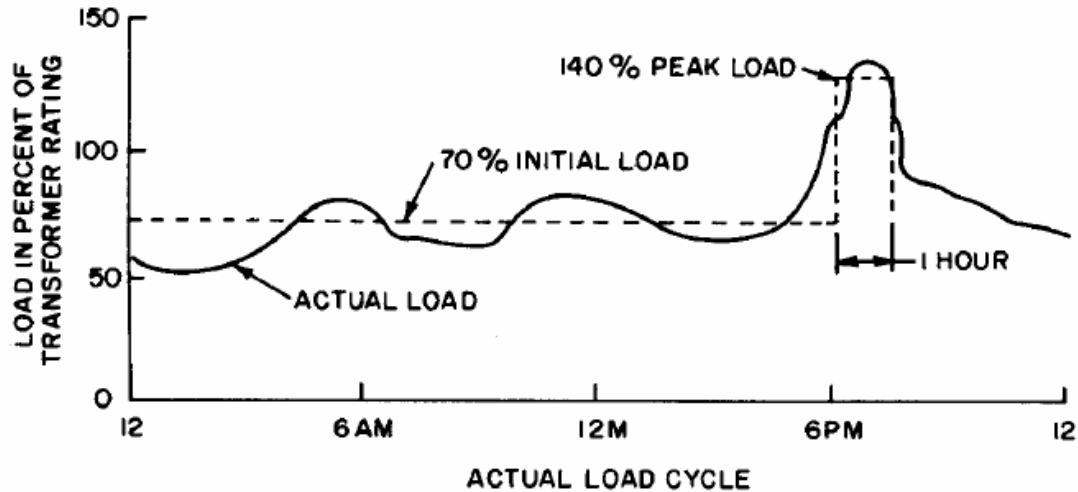


Figure 3—Example of actual load cycle and equivalent load cycle

7.1.3 Equivalent peak load

Equivalent peak load for the usual load cycle is the rms load obtained by Equation (5) 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 over-estimated, the rms peak value may be considerably below the maximum peak demand. To guard against overheating due to high, brief overloads during the peak overload, the rms value for the peak load period should not be less than 90% of the integrated 1/2 h maximum demand.

7.1.4 Equivalent continuous prior load

The equivalent continuous prior load is the rms load obtained by Equation (5) over a chosen period of the day. Experience indicates that quite satisfactory results are obtained by considering the 12 h periods preceding and following the peak and by selecting the larger of the two rms values so produced. Time intervals (t) of 1 h are suggested as a further simplification of the equation, which for a 12 h period becomes Equation (6). The dashed line in Figure 3 shows the equivalent load cycle constructed from the actual load cycle.

$$\text{Equivalent continuous 12 h prior load} = 0.29 \left[L_1^2 + L_2^2 + \dots + L_{12}^2 \right]^{0.5} \quad (6)$$

where

$L_1, L_2, \dots$ is various load steps in %, per unit, or in actual kVA or current

7.2 Calculation of temperatures

7.2.1 General

The method given here for calculation of oil and winding temperatures for changes in load ~~is simplified and~~ requires no iterative procedures. The exponents, m and n , approximately account for changes in load loss and oil viscosity caused by changes in temperature. Values for the exponents used in these equations are shown in Table 4. Exact values of the exponents for specific transformers may be determined by overload test procedures in IEEE Std C57.119 [G6].⁶

An alternate method, which requires computer calculation procedures, is given in Annex G. This method is more exact in accounting for changes in load loss and oil viscosity caused by changes in resistance and oil temperature, respectively. The effect of a variable ambient temperature is also considered. This method should produce a greater accuracy in loading capability if accurate methods of determining load, ambient temperature, tap position, and the cooling mode in operation are utilized.

7.2.2 Components of temperature

The hottest-spot temperature is assumed to consist of three components given by the following equation:

$$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_H \quad (7)$$

where

Θ_H is the winding hottest-spot temperature, °C

Θ_A is the average ambient temperature during the load cycle to be studied, °C

$\Delta\Theta_{TO}$ is the top-oil rise over ambient temperature, °C

$\Delta\Theta_H$ is the winding hottest-spot rise over top-oil temperature, °C

The top-oil temperature is given by the following equation:

$$\Theta_{TO} = \Theta_A + \Delta \Theta_{TO} \quad (8)$$

where

Θ_{TO} is the top-oil temperature, °C

Θ_A is the average ambient temperature during the load cycle to be studied, °C

$\Delta \Theta_{TO}$ is the top-oil rise over ambient temperature, °C

⁶ The numbers in brackets combined with the letter “G” correspond to those of the bibliography in Annex G.

The temperature calculations assume a constant ambient temperature. The effect of a variable ambient may be conservatively considered as follows:

- a) For ambient temperatures that increase during the load cycle, the instantaneous ambient should be used when considering load cycles.
- b) For decreasing ambient temperatures, the maximum ambient during a long prior cycle of about 12 h should be used.

7.2.3 Top-oil rise over ambient

The top-oil temperature rise at a time after a step load change is given by the following exponential expression containing an oil time constant:

$$\Delta \Theta_{TO} = (\Delta \Theta_{TO,U} - \Delta \Theta_{TO,i}) \left(1 - e^{-\frac{t}{\tau_{TO}}} \right) + \Delta \Theta_{TO,i} \quad (9)$$

where

$\Delta \Theta_{TO}$ is the top-oil rise over ambient temperature, °C

$\Delta \Theta_{TO,U}$ is the ultimate top-oil rise over ambient temperature for load L , °C

$\Delta\Theta_{TO,I}$ is the initial top-oil rise over ambient temperature for $t = 0$, °C exp is the base of natural logarithm

τ_{TO} is the oil time constant of transformer for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise, h

For the two-step overload cycle with a constant equivalent prior load the initial top-oil rise is given by the following:

where

$\Delta\Theta_{TO,I}$ is the initial top-oil rise over ambient temperature for $t = 0$, °C

$\Delta\Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

K_I is the ratio of initial load L to rated load, per unit

N is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4.

R is the ratio of load loss at rated load to no-load loss on the tap position to be studied

For the multi-step load cycle analysis with a series of short-time intervals, Equation (9) is used for each load step, and the top-oil rise calculated for the end of the previous load step is used as the initial top-oil rise for the next load step calculation.

The ultimate top-oil rise is given by the following equation:

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R} \left[\frac{(K_U^2 R + I)}{(R + I)} \right]^n \quad (11)$$

where

$\Delta\Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

$\Delta\Theta_{TO,U}$ is the ultimate top-oil rise over ambient temperature for load L , °C

K_U is the ratio of ultimate load L to rated load, per unit

n is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4.

R is the ratio of load loss at rated load to no-load loss on the tap position to be studied

Equation (11) is used to calculate the ultimate oil rise for each load step. Except for very long duration constant loads, the ultimate top-oil rise calculated by Equation (11) is never reached.

7.2.4 Oil time constant

The thermal capacity is given by the following equation for the ONAN and ONAF cooling modes:

$$C = 0.1323 (\text{weight of core and coil assembly in kilograms}) \quad (12A) \\ + 0.0882 (\text{weight of tank and fittings in kilograms}) \\ + 0.3513 (\text{liters of oil})$$

or

$$C = 0.06 (\text{weight of core and coil assembly in pounds}) \quad (12B) \\ + 0.04 (\text{weight of tank and fittings in pounds}) \\ + 1.33 (\text{gallons of oil})$$

The derivation of the exponential heating equation is based on the average temperature rise of the lumped mass. In the case of the transformer this would be the average oil temperature. However, the top oil is the variable measured by temperature indicators or thermocouples during thermal tests. In Equation (12A) for the thermal capacity, two-thirds of the weight of the tank and 86% of the specific heat of the oil was used.

For forced-oil cooling modes either directed or non-directed the thermal capacity is given by the following:

$$C = 0.1323 (\text{weight of core and coil assembly in kilograms}) \quad (13A) \\ + 0.1323 (\text{weight of tank and fittings in kilograms}) \\ + .5099 (\text{liters of oil})$$

or

$$C = 0.06 (\text{weight of core and coil assembly in pounds}) \quad (13B) \\ + 0.06 (\text{weight of tank and fittings in pounds}) \\ + 1.93 (\text{gallons of oil})$$

For the calculation of the time constant, the weight of the tank and fittings to be used is only those portions that are in contact with heated oil. Some transformers may have cabinetry and tank base construction with substantial weight that does not contribute to the thermal mass in determination of the oil rise time constant.

The top-oil time constant at rated kVA is given by the following:

$$\tau_{TO,R} = \frac{C \Delta \Theta_{TO,R}}{P_{T,R}} \quad (14)$$

where

C is the thermal capacity of the transformer, W-h/°C

$P_{T,R}$ is the total loss at rated load, W

$\Delta \Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

$\tau_{TO,R}$ is the time constant for rated load beginning with initial top-oil temperature rise of 0 °C, h

The top-oil time constant is

$$\tau_{TO} = \tau_{TO,R} \frac{\left(\frac{\Delta \Theta_{TO,U}}{\Delta \Theta_{TO,R}} \right) - \left(\frac{\Delta \Theta_{TO,i}}{\Delta \Theta_{TO,R}} \right)}{\left(\frac{\Delta \Theta_{TO,U}}{\Delta \Theta_{TO,R}} \right)^{\frac{1}{n}} - \left(\frac{\Delta \Theta_{TO,i}}{\Delta \Theta_{TO,R}} \right)^{\frac{1}{n}}} \quad (15)$$

where

n is an empirically derived exponent used to calculate the variation of $\Delta \Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4.

$\Delta \Theta_{TO,i}$ is the initial top-oil rise over ambient temperature for $t = 0$, °C

$\Delta \Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

$\Delta \Theta_{TO,U}$ is the ultimate top-oil rise over ambient temperature for load L , °C

τ_{TO} is the oil time constant of transformer for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise, h

$\tau_{TO,R}$ is the time constant for rated load beginning with initial top-oil temperature rise of 0 °C, h

In the derivation of Equation (9) it was assumed that the top-oil temperature rise $\Delta\Theta_{TO}$ is directly proportional to the heat loss q , or in equation form,

$$\Delta\Theta_{TO} = Kq^n$$

where

n is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4.

K is the ratio of load L to rated load, per unit

q is the heat loss, W

$\Delta\Theta_{TO}$ is the top-oil rise over ambient temperature, °C

If the exponent $n = 1.0$, the time constant given by Equation (14) and the exponential Equation (9) is correct for any load and any starting temperature. If n is less than 1, the equation is incorrect and the time constant must be modified as shown in Equation (15) for different overload cycles. Equation (15) was developed to give a corrected time constant (for case of $n < 1$) to use in the exponential equation that gave the same rate of change of initial temperature rise and the same final temperature rise if the overload continued indefinitely; however, intermediate temperatures may vary somewhat from actual.

If n is equal to 1.0, 63% of the temperature change occurs in a length of time equal to the time constant regardless of the relationship of initial temperature rise and ultimate temperature rise. If n is not unity, the temperature change in a similar time interval will be different, depending on both initial temperature rise and ultimate temperature rise.

7.2.5 Winding hot-spot rise

Transient winding hottest-spot temperature rise over top-oil temperature is given by

$$\Delta \Theta_H = (\Delta \Theta_{H,U} - \Delta \Theta_{H,i}) \left(1 - e^{-\frac{t}{\tau_w}} \right) + \Delta \Theta_{H,i} \quad (16)$$

where

t is the duration of load, h

$\Delta \Theta_H$ is the winding hottest-spot rise over top-oil temperature, °C

$\Delta \Theta_{H,U}$ is the ultimate winding hottest-spot rise over top-oil temperature for load L , °C

$\Delta \Theta_{H,i}$ is the initial winding hottest-spot rise over top-oil temperature for $t = 0$, °C

τ_w is the winding time constant at hot spot location, h

The initial hot-spot rise over top oil is given by

$$\Delta \Theta_{H,i} = \Delta \Theta_{H,R} K_i^{2m} \quad (17)$$

where

K_i is the ratio of initial load L to rated load, per unit

m is an empirically derived exponent used to calculate the variation of $\Delta \Theta_H$ with changes in load.

The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and oil viscosity with changes in load. See Table 4.

$\Delta \Theta_{H,i}$ is the initial winding hottest-spot rise over top-oil temperature for $t = 0$, °C

$\Delta \Theta_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C

The ultimate hot-spot rise over top oil is given by

$$\Delta \Theta_{H,U} = \Delta \Theta_{H,R} K_u^{2m} \quad (18)$$

where

K_U is the ratio of ultimate load L to rated load, per unit

m is an empirically derived exponent used to calculate the variation of $\Delta \Theta_H$ with changes in load. The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and oil viscosity with changes in load. See Table 4.

$\Delta \Theta_{H,U}$ is the ultimate winding hottest-spot rise over top-oil temperature for load L , °C

$\Delta \Theta_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C

The rated value of hot-spot rise over top oil is given by

$$\Delta \Theta_{H,R} = \Delta \Theta_{H/A,R} - \Delta \Theta_{TO,R} \quad (19)$$

where

$\Delta \Theta_{H/A,R}$ is the winding hot spot rise over ambient at rated load on the tap position to be studied, °C

$\Delta \Theta_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C

$\Delta \Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

The value of the winding hot-spot rise over ambient $\Delta \Theta_{H/A,R}$ is obtained in the following manner, in order of preference:

- By actual test using imbedded detectors
- Calculated value supplied by manufacturer on test report, or
- Assume $\Delta \Theta_{H/A,R} = 80$ °C for 65 °C average winding rise and 65 °C for 55 °C average winding rise

The value of the top-oil rise over ambient $\Delta \Theta_{TO,R}$ is determined by

- Actual test per IEEE Std C57.12.90, or
- Calculated value supplied by the manufacturer on the test report

The winding time constant is the time it takes the winding temperature rise over oil temperature rise to reach 63.2% of the difference between final rise and initial rise during a load change. The winding time constant may be estimated from the resistance cooling curve during thermal tests or calculated by the manufacturer using the mass of the conductor materials. The winding time constant varies with the oil viscosity and the exponent m . For moderate overloads it is conservative to neglect the winding time constant and assume the winding hot-spot rise over top oil is given by Equation (18).

7.2.6 Exponents for temperature rise equations

The suggested exponents for use in the temperature rise equations are given in Table 4.

Table 4—Exponents used in temperature determination equations

Type of cooling	m	n
ONAN	0.8	0.8
ONAF	0.8	0.9
Non-directed OFAF or OFWF	0.8	0.9
Directed ODAF or ODWF	1.0	1.0

*Other values of exponents may be used if substantiated by design and test data.

7.2.7 Adjustment of test data for different tap position

If it is desired to adjust the test report data for operation on a no-load tap position other than that reported on the test report, the following equations may be used. The prime symbol (') indicates values at the different tap position.

Top-oil rise over ambient:

$$\Delta \Theta'_{TO,R} = \Delta \Theta_{TO,R} \left[\frac{P'_{T,R}}{P_{T,R}} \right]^n \quad (20)$$

where

n is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load.

The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4.

$P_{T,R}$ is the total loss at rated load, W

$P'_{T,R}$ is the total loss at rated load on a different tap position, W

$\Delta\Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

$\Delta\Theta'_{TO,R}$ is the top-oil rise over ambient temperature at rated load on a different tap position, °C

Hottest spot rise over top oil:

$$\Delta\Theta'_{H,R} = \Delta\Theta_{H,R} \left[\frac{I'_R}{I_R} \right]^{2m} \quad (21)$$

where

I_R is rated current

I'_R is rated current for a different tap position

m is an empirically derived exponent used to calculate the variation of $\Delta\Theta_H$ with changes in load.

The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and oil viscosity with changes in load. See Table 4.

$\Delta\Theta_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C

$\Delta\Theta'_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on a different tap position, °C

Time constant at rated load:

$$\tau'_{TO,R} = \frac{C \Delta\Theta_{TO,R}}{P'_{T,R}} \quad (22)$$

where

C is the thermal capacity of the transformer, W-h/°C

P'_{T,R} is the total loss at rated load on a different tap position, W

$\Delta\Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C

$\tau'_{TO,R}$ is the time constant for rated load for a different tap position beginning with initial top-oil temperature rise of 0 °C, h

7.3 Computer calculation of loading capability

Due to the wide variations in transformer characteristics typical loading capability tables are not published in this guide. The equations given in Clause 5 and Clause 7 may be used to develop a computer program that calculates the loading capability for a specific transformer design. A suggested flow chart is shown in Table 4. The program should compute and print the maximum peak load that can be impressed on a transformer and meet specified limitations. In addition, the computer program should calculate the top-oil and hottest-spot temperatures as a function of time for a repetitive 24 h load cycle. The total loss of insulation life for a 24 h load cycle should also be calculated.

Input to the program should consist of the following:

- a) Transformer characteristics (loss ratio, top-oil rise, bottom-oil rise, hottest-spot rise, total loss, gallons of oil, weight of tank and fittings) (all at rated load)
- b) Ambient temperatures
- c) Initial continuous load
- d) Peak load durations and the specified daily percent loss of life
- e) Repetitive 24 h load cycle if desired

A systematic convergence process may be used to obtain the highest allowable peak load. An initial trial is made with an assumed peak load midway between the minimum continuous load and maximum permitted peak load (300% for distribution transformers, 200% for power transformers). Using this peak load, aging calculations are made at varying time intervals (depending on the time duration of the peak load) during the 24 h, to determine the total daily insulation aging imposed by the load cycle. A comparison is made between the calculated values and the limiting values, (top-oil temperature, hot-spot temperature, or specified percent loss of life). Depending on the results, the peak value is changed and the calculation repeated until the calculated value of the total percent loss of life above normal is within $\pm 4\%$ of the desired value. At this point, the peak load and corresponding values of peak hottest-spot temperature, peak top-oil temperature, total percent loss of life, and the specified percent loss of life are printed out.

7.4 Bibliography for Clause 7

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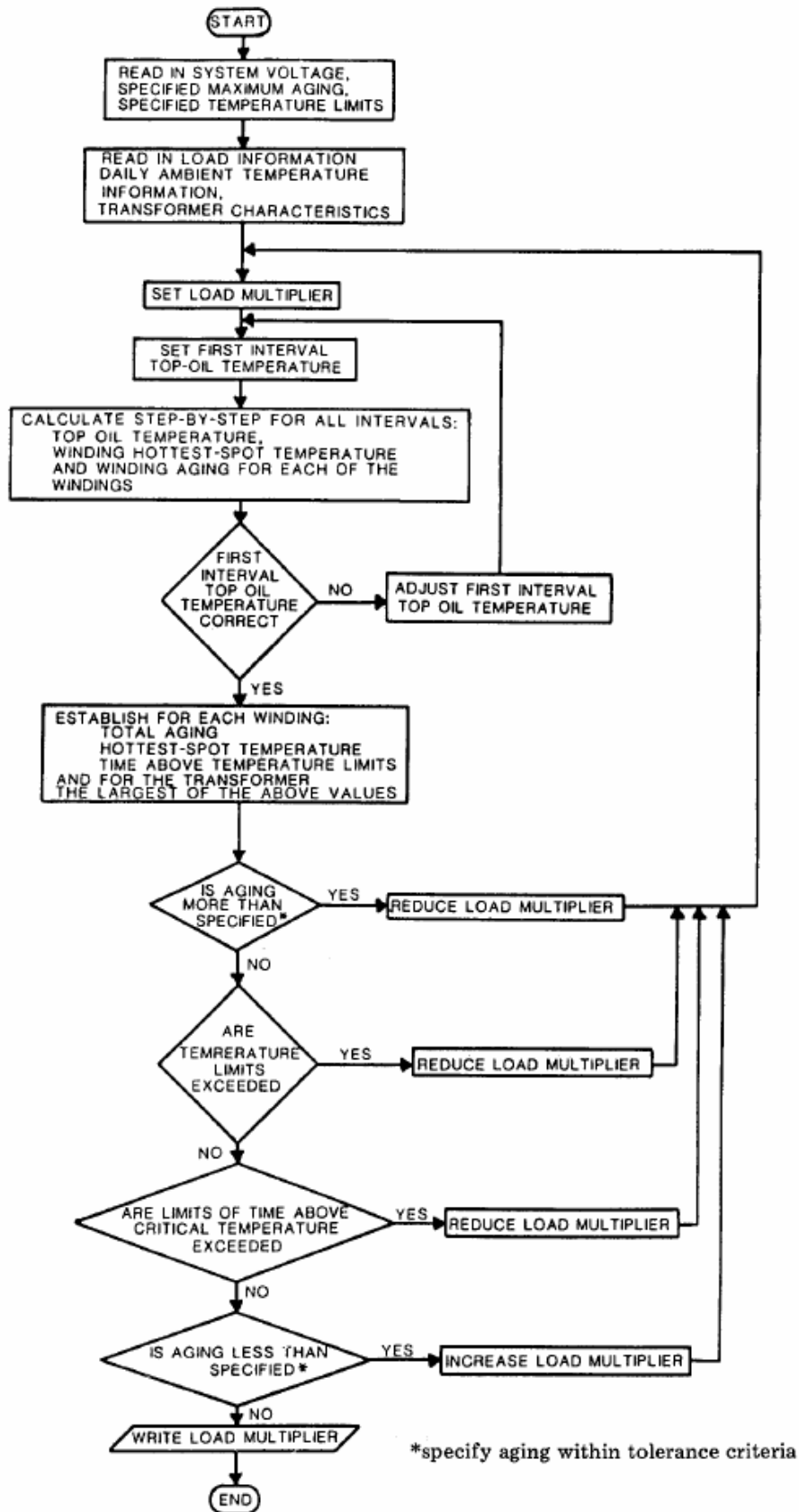


Figure 4 —Logic diagram for computer program

8. Loading of distribution transformers and step-voltage regulators

8.1 Life expectancy

8.1.1 General

Distribution transformer and voltage regulator life expectancy at any operating temperature is not accurately known. The information given regarding loss of insulation life at elevated temperatures 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 data may affect future revisions of this guide. The word conservative as used above is used in the sense that the expected loss of insulation life for a single overload cycle will not be greater than the amount stated.

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 any 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. 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 or voltage regulator 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 heating resulting from a heavy overload or to large electromagnetic forces resulting from short circuit, may disturb the mechanically weak insulation such that turn-to-turn or layer-to-layer failure will result.

The recommendations of this guide are based upon the life expectancy curve of Figure 1, which relates to the insulation system, but does not account for such factors as deterioration of gaskets, rusting of tanks, etc., that are induced by exposure to the elements of the weather in normal operations.

8.1.2 Normal life expectancy

The basic loading of a distribution transformer or voltage regulator for normal life expectancy is continuous loading at rated output when operated under usual service conditions as indicated in 4.1 of IEEE Std C57.12.00-~~1993~~-2010 and 4.1 of IEEE Std C57.15-2009. It is assumed that operation under these conditions is equivalent to operation in a constant 30 °C ambient temperature. The hottest-spot conductor temperature is

the principal factor in determining life due to loading. Direct temperature measurement of the hottest-spot may not be practical on commercial designs. The indicated hottest-spot temperatures have therefore been obtained from tests made in the laboratory and mathematical models. The hottest-spot temperature at rated load is the sum of the average winding temperature and a hottest-spot allowance, usually 15 °C. Normal life expectancy will result from operating continuously with hottest-spot conductor temperature of 110 °C or an equivalent daily transient cycle. For mineral oil-immersed transformers [and voltage regulators](#) operating continuously under the foregoing conditions this temperature has been limited to a maximum of 110 °C. Normal life expectancy of transformer [and voltage regulator](#) insulation using different criteria is given in Table 1. Distribution and power transformer model tests indicate that the normal life expectancy at a continuous hottest-spot temperature of 110 °C is 20.55 years.

8.2 Limitations

8.2.1 General

When loading distribution transformers [and voltage regulators](#) above nameplate rating, other limitations may be encountered. Among these limitations are oil expansion, pressure in sealed units, and the thermal capability of bushings; leads, tap changers, or associated equipment such as cables, reactors, circuit breakers, fuses, disconnecting switches, and current transformers. Any of these items may limit the loading to less than the capability of the winding insulation. Manufacturers should, therefore, be consulted before loading transformers [or voltage regulators](#) above nameplate rating. Operation at hottest-spot temperatures above 140 °C may cause gassing in the solid insulation and the oil. Gassing may produce a potential risk to the dielectric strength integrity of the transformer [or voltage regulator](#) and this risk should be considered when the guide is applied.

Distribution transformers are sometimes installed in subsurface manholes and vaults of minimum size with natural ventilation through roof gratings. This type of installation results in a higher ambient temperature than the outdoor air. The amount of increase depends on the design of the manholes and vaults, net opening area of the roof gratings, and the adjacent subsurface structures. Therefore, the increase in effective ambient temperature for expected transformer losses must be determined before loading limitations can be estimated.

The separate heating effects of loading a distribution transformer [or voltage regulator](#), and of solar radiation, may each result in an enclosure surface temperature high enough to present a hazard to personnel who might come in contact with the enclosure surface where unlimited access to the transformer [or voltage regulator](#) exists (such as certain pad-mounted units).