

IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Rated in Excess of 100 MVA (65 °C Winding Rise)

Sponsor
Transformers Committee
of the
IEEE Power Engineering Society

Approved March 21, 1991
IEEE Standards Board

Abstract: This guide covers modern power transformers rated above 100 MVA, three-phase equivalent, and 65 °C rise. The general approach is tutorial. Four different types of loading, that is, normal life expectancy loading, planned loading beyond nameplate rating, long-time emergency loading, and short-time emergency loading, are considered. The various effects of loading a transformer in excess of its nameplate rating are discussed. Temperature and maximum loading limitations are suggested.

Keywords: emergency loading, loading, mineral-oil-immersed power transformers, nameplate rating, power transformers, temperature, transformers

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

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Printed in the United States of America

ISBN 1-55937-131-5

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Foreword

(This Foreword is not a part of IEEE C57.115-1991, IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Rated in Excess of 100 MVA (65 °C Winding Rise).)

This guide for loading mineral-oil-immersed power transformers rated in excess of 100 MVA has been developed to cover modern power transformers rated above 100 MVA, three-phase equivalent, and 65 °C rise. It was prepared to make available the best engineering knowledge on subjects of concern to the industry.

The general approach in this guide is tutorial. Four different types of loading

- (1) Normal Life Expectancy Loading
- (2) Planned Loading Beyond Nameplate Rating
- (3) Long-Time Emergency Loading
- (4) Short-Time Emergency Loading

are considered. The various effects of loading a transformer in excess of its nameplate rating are discussed. Temperature and maximum loading limitations are suggested.

The equations given in Section 3 are from IEEE C57.92-1981 and have been in general industry use for many years. However, questions have now been raised on the accuracy of these equations, and a task force has been set up within the IEEE Transformers Committee to review the state of the art in this area.

One of the major concerns in this guide is based on the evidence that a reduction in dielectric strength may occur due to the formation of free gas bubbles at temperatures above 140 °C in the insulated conductors. A potential risk could occur in the operation of the transformer above 140 °C. This risk is a function of the amount of free gas generated because it can cause dielectric failure during an overvoltage condition and possibly at rated power frequency voltage. In the event of generation of free gas within the insulation, dielectric strength will be degraded while the gas is present. However, this fact does not necessarily indicate that any permanent dielectric degradation would occur.

Tutorial appendixes covering gas evolution, ancillary parts, methods of calculating acceptable loading levels, and philosophy applicable to older transformers are included.

Comments on this guide are welcomed and should be addressed to the

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IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Rated in Excess of 100 MVA (65 °C Winding Rise)

1. Scope

This guide covers general recommendations for loading mineral-oil immersed power transformers manufactured in accordance with IEEE C57.12.00-1987 [1]¹ and having a maximum nameplate rating in excess of 100 MVA (three phase) or 33 1/3 MVA (single phase). Such transformers have an average winding rise of 65 °C maximum and a hottest-spot rise of 80 °C maximum at rated load.

NOTE: When this guide is to be used for transformers purchased prior to publication of the guide, the applicability of 2.5 and 4.3 should be checked with the manufacturer. Also see Appendix D.

2. General

2.1 References

[1] IEEE C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.²

[2] IEEE C57.91-1981, IEEE Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 kVA and Less With 65 °C or 55 °C Average Winding Rise.

¹ The numbers in brackets correspond to the references listed in 2.1.

² IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[3] IEEE C57.92-1981, IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Up to and Including 100 MVA With 55 °C or 65 °C Average Winding Rise.

2.2 Effect of Loading Beyond Nameplate Rating. Application 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 rules the application of which will minimize the risks to the fullest extent that present state-of-the-art knowledge permits. While aging and long-time mechanical deterioration of winding insulation have been the basis for the loading of power transformers for many years, it is recognized that there are additional factors which may involve greater risk for transformers of higher megavoltampere and voltage ratings. The risk areas which should be considered when loading large transformers beyond nameplate rating are broadly defined as follows:

(1) 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. Since the free gas is generated in the insulation near the conductor, where dielectric stresses are high, the risk of electrical failure is increased. This is principally a temporary risk which lasts for the period that the gas bubbles exist in the insulation. Following the period of overheating the gas bubbles will dissolve in the oil and full

dielectric integrity will return unless partial insulation breakdown, which may produce carbonized tracking, occurs while the free gas is present. See Appendix A for further discussion.

(2) Evolution of free gas from insulation adjacent to metallic structural parts linked by electromagnetic flux produced by winding or lead currents may also reduce dielectric strength. Since these parts are not located in the regions of high dielectric stress, evolved free gas has to migrate to areas of the insulation system where dielectric stresses are at more critical levels before they can have significant impact on dielectric integrity. In the course of migration, the free gas bubbles tend to be dissolved into the oil. As a consequence, slightly higher hottest-spot temperatures may be tolerated for other metallic parts than for insulated conductors. Any risk of reduced dielectric integrity lasts essentially for the period of free-gas evolution.

(3) Aging or deterioration of conductor insulation as a function of time and temperature is the most widely recognized permanent effect of power transformer loading. Aging is fully described in IEEE C57.92-1981 [3]. Over a relatively long period of time, there will be a cumulative degradation of the electrical and mechanical properties of the conductor insulation, which could result in failure. Loss of life calculations may be made as described in IEEE C57.92-1981 [3]. 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, which increase with megavoltampere rating.

(4) Structural insulation materials also suffer cumulative permanent degradation of mechanical properties as a function of time-temperature history. In addition, there is some degree of temporary reduction of mechanical capability at elevated temperatures. These effects are expected to be of major concern during periods of transient over-current (short-circuit faults) when mechanical forces reach their highest levels.

(5) Thermal expansion of conductors, insulation materials, or structural parts at high temperatures may result in permanent deformations which could contribute to mechanical or dielectric failures.

(6) Pressure build-up with bushings for currents above rating could result in leaking gaskets, loss of oil, and ultimate dielectric failure. See Appendix B for further discussion.

(7) 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 Appendix B for further discussion.

(8) Auxiliary equipment internal to the transformer, such as reactors and current transformers, may also be subject to some of the risk identified above. See Appendix B for further discussion.

(9) When the temperature of the top oil exceeds 105 °C (65 °C rise over 40 °C ambient according to IEEE C57.12.00-1987 [1]), there is a possibility that oil expansion will result in an oil loss through the pressure relief device. The overflow may also create problems with the oil preservation system.

2.3 Types of Loading and Their Interrelationship. Loads in excess of nameplate rating may be applied to transformers on four different time-temperature bases. An increased risk is probable for each successive loading with its attendant increased temperature and duration. The applicable times and temperature ranges are shown in Table 1, maximum temperatures in Table 2, and examples of loads which fall within these categories are illustrated in Fig 1 and described in 2.3.5. The four load types are described in 2.3.1 through 2.3.4.

2.3.1 Normal Life Expectancy Loading. Normal life expectancy loading is loading that may exceed nameplate rating provided the maximum conductor hottest-spot and maximum top-oil temperatures permitted in IEEE C57.12.00-1987 [1] are not exceeded. Other metallic temperatures reached under this loading will not be of concern. This loading may be continued indefinitely and is considered risk-free with respect to the risks outlined in 2.2.

2.3.2 Planned Loading Beyond Nameplate Rating. Planned loading beyond nameplate rating results in either the conductor hottest-spot or top-oil temperature exceeding those suggested in Table 2 for normal life expectancy

Table 1
Coordination of Suggested Loading Type, Duration, and Temperature Range

Type of Loading	Daily Duration in the Specified Hottest-Spot Temperature Range (hour)	Insulated** Conductor Hottest-Spot Temperature Range (°C)
Normal life expectancy loading	*	110–120
Planned loading beyond nameplate rating	4	120–130
Long-time emergency loading	4	120–130
	6	130–140
Short-time emergency loading	4	120–130
	1	130–180
	6	130–140

*Since loss-of-life is cumulative, transformers may be operated above 110 °C hottest-spot temperature (not to exceed 120 °C) for short periods provided they are operated for much longer periods at temperatures below 110 °C.

**See 2.3.5 for explanations.

Table 2
Suggested Maximum Temperature Limits for the Four Types of Loading

	Normal Life Expectancy Loading (°C)	Planned Loading Beyond Nameplate Rating (°C)	Long-Time Emergency Loading (°C)	Short-Time Emergency Loading (°C)
Insulated conductor hottest-spot temperature	120*	130	140	180**
Other metallic hot-spot temperature (in contact and not in contact with insulation)	140	150	160	200
Top-oil temperature	105	110	110	110

*110 °C on a continuous 24 h basis.

**Operation at insulated conductor hottest-spot temperatures above 140 °C may cause gassing in the solid insulation and oil. Gassing may produce a potential risk to the dielectric strength of the transformer. This risk should be considered when the guide is applied.

loading, and is accepted by the user as a normal, planned-for repetitive load.

Suggested conductor hottest-spot temperatures coordinated with daily durations are presented in Table 1.

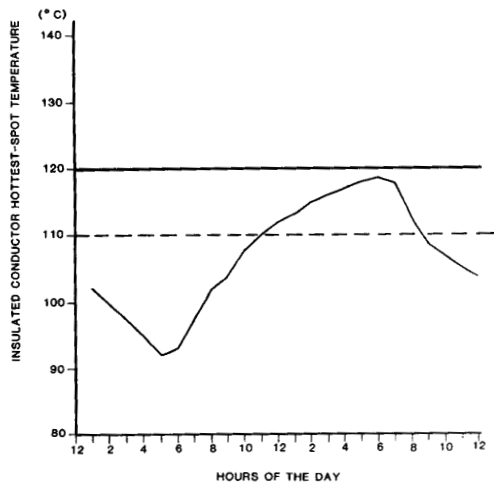
This loading occurs with no system outages and some risk is associated with it as outlined in 2.2.

2.3.3 Long-Time Emergency Loading. Long-time emergency loading results from the prolonged outage of some system element and causes either the conductor hottest-spot or the top-oil temperature to exceed those suggested for planned loading beyond nameplate rating. This is not a normal operating condition, but may persist for some time. It is expected that such occurrences will be rare.

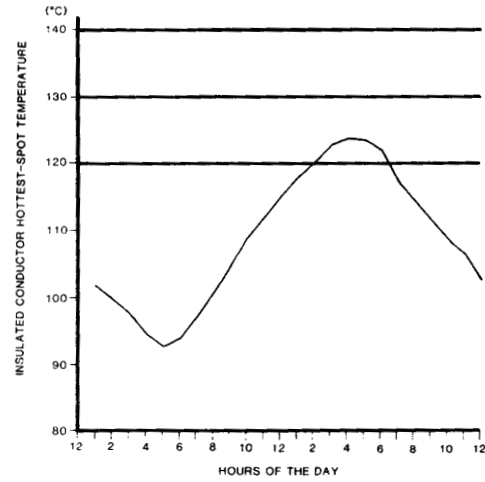
Suggested conductor hottest-spot temperatures coordinated with daily durations are presented in Table 1. Top-oil temperature should not exceed 110 °C at any time.

This loading results from a system outage and is more severe than planned loading beyond nameplate rating. Both loss of insulation life and risk are greater than under planned loading beyond nameplate rating. It is expected that there will be only two or three such occurrences in the life of a transformer.

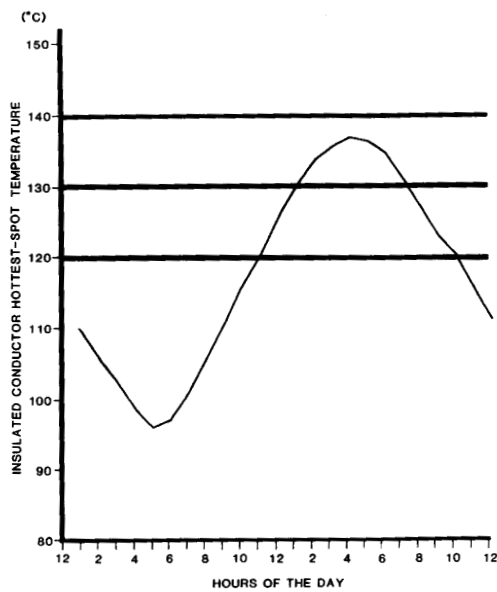
2.3.4 Short-Time Emergency Loading. Short-time emergency loading is an unusually heavy loading brought about by the occurrence of one or more unlikely events which seriously disturb normal system loading and cause either the conductor hottest-spot or top-oil tempera-



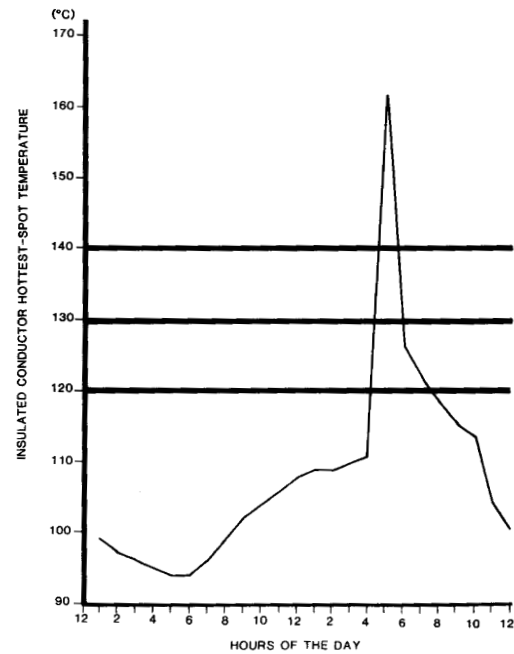
(a)



(b)



(c)



(d)

Fig 1
(a) Normal Life Expectancy Loading (b) Planned Loading Beyond Nameplate Rating (c) Long-Time Emergency Loading (d) Short-Time Emergency Loading

ture to exceed the temperature limits suggested for planned loading beyond nameplate rating. Acceptance of these conditions for a short time may be preferable to other alternatives. It is expected that this type of loading will be reduced to long-time emergency loading in not more than 1 h.

Suggested conductor hottest-spot temperatures coordinated with daily durations are presented in Table 1. Top-oil temperature should not exceed 110 °C at any time.

This type of loading, with its greater risk, is expected to occur rarely.

2.3.5 Interrelationship of Loading Types. Examples of hottest-spot temperature profiles for the four types of loading defined in 2.3.1 to 2.3.4 are illustrated in Fig 1(a) through 1(d). Note that for each higher temperature, a higher risk loading condition can be assumed to be additive to any lower risk condition accepted by the user except for the short-time emergency loading. For further clarification a brief description of the last three loading types are described below.

Planned loading beyond nameplate rating defines a condition wherein a transformer is so loaded that its hottest-spot temperature is in the temperature range of 120 °C–130 °C for a maximum of 4 h daily. The characteristics of this type of loading are no system outages, regular and comparatively frequent occurrences, and there is some risk. Figure 1(b) illustrates a planned loading beyond nameplate rating profile.

Long-time emergency loading defines a condition wherein a transformer is so loaded that its hottest-spot temperature is in the temperature range of 120 °C–130 °C for a maximum of 4 h and in the temperature range of 130 °C–140 °C for a maximum of 6 h daily. The characteristics of this type of loading are one long time outage of a transmission system element, two or three occurrences over the normal lifetime of the transformer, each occurrence may last several months, and the risk is greater than planned loading beyond nameplate rating. Figure 1(c) illustrates a long-time emergency loading profile. Note that while the hottest-spot temperature is increasing with time, it is in the temperature range of 120 °C–130 °C for approximately 2 h. The hottest-spot temperature is in the temperature range of 130 °C–140 °C for 6 h. On the descending part of the curve the hottest-spot temperature is once

again in the temperature range of 120 °C–130 °C for approximately 2 h resulting in a total of 4 h in the temperature range of 120 °C–130 °C for the 24 h period. The hottest-spot temperature is allowed to exceed 120 °C for a maximum of 10 h.

Short-time emergency loading defines a loading condition wherein a transformer is so loaded that its hottest-spot temperature is in the temperature range of 120 °C–130 °C for a maximum of 4 h, in the temperature range of 130 °C–180 °C and back to 140 °C for 1 h, and in the temperature range of 130 °C–140 °C for a maximum of 6 h. The characteristics of this type of loading are a series of unlikely conditions on the transmission system (2nd or 3rd contingency), one or two occurrences over the normal lifetime of the transformer, each occurrence is 1 h duration or less, and the risk is greater than for long-time emergency loading. Figure 1(d) illustrates a short-time emergency loading profile. This figure presents a temperature curve that has leveled off for the day until about 4 pm when a system condition occurs which loads the transformer so that its hottest-spot temperature rises rapidly to 163 °C in 1 h. Note that Fig 1(d) presents a loading that is within the spirit of the guide. On the rising side of the curve the hottest-spot temperature is in the range of 120 °C–130 °C for approximately 15 min. The hottest-spot temperature continues rising from 130 °C toward 180 °C and back to 140 °C in approximately 1 h while peaking at approximately 163 °C. On the descending portions of the curve, the hottest-spot temperature is in the 130 °C–140 °C range for approximately one-half hour and once again in the temperature range of 120 °C–130 °C for 2 h, resulting in a total of 2 h 15 min in the temperature range of 120 °C–130 °C for the 24 h period. The total time above 120 °C is 3 h 30 min for this example as opposed to the 11 h maximum permitted.

2.3.6 Risk Considerations. Normal life expectancy loading is considered to be risk free; however, the remaining three types of loading have associated with them some indefinite level of risk. Specifically, the level of risk is based on the quantity of free gas and voltage. The presence of free gas as outlined in 2.2 can cause dielectric failure during an overvoltage condition and possibly at rated power frequency voltage. The Task Force has selected

the temperature levels and time durations shown in Table 1 for each of the defined types of loading which they subjectively believe will result in an acceptable degree of risk for the special circumstances which require loading beyond nameplate rating. A scientific basis for the users' evaluation of the degree of risk is not available at this time. Current research in the area of model testing has not established sufficient quantitative data on the relationship between conductor temperature, length of time at that temperature, and reduction in winding dielectric strength. Additionally, there are other important factors which may affect any reduction, such as moisture content of the winding insulation and rate of rise of conductor temperature.

2.4 Temperature Limitations. It is suggested that the temperature limitations in Table 2 should not be exceeded during any overload event.

2.5 Maximum Loading Limitations. Maximum load capacity which a transformer user plans to utilize on a planned or emergency basis, or both, should be included in the specifications at the time of purchase. The following information should be given:

- (1) Prior steady-state load, percent of maximum rating
- (2) Ambient temperature, °C
- (3) Maximum load, percent of maximum rating
- (4) Duration of maximum load, hours
- (5) Type of loading, planned or emergency, long-time or short-time, or acceptable limiting temperatures

- (6) Acceptable loss-of-life, percent of normal life, per occurrence

More than one set of loading conditions may be defined or a 24 h load cycle (with associated ambient temperatures) may be given.

In the absence of specified loading capabilities, the maximum load and duration limits shown in Table 3 are suggested for transformers purchased after the publication of this guide. These suggestions apply to loading beyond nameplate rating on a long-time emergency basis for generator step-up transformers and a short-time emergency basis for system-tie or substation transformers.

Other combinations of load, duration, prior load, and ambient temperature may be used, if the maximum loads shown in Table 3 and the insulated conductor hottest-spot temperature limits of 2.4 are not exceeded. Tap changers, bushings, leads, and other ancillary equipment will not normally restrict loading to levels below those given in Table 3, but the user may wish to specify that ancillary equipment not restrict loading to levels below those permitted by the insulated conductor and other metallic part hot-spots.

2.6 Information for User Calculations. If the user intends to perform calculations to help determine the loading capability of a transformer, the user should request information of the following type in his specification:

- (1) Top-oil temperature rise over ambient temperature
- (2) Bottom-oil temperature rise over ambient temperature
- (3) Average conductor temperature rise over ambient temperature

Table 3
Suggested Design Limits for
New Transformers when Loading Information Is Not Supplied

Application	Maximum Load (% of Maximum Rating) (%)	Duration* (hours)	Insulated Conductor Maximum Hottest-Spot Temperature Not to Exceed (°C)
Generation step-up	110	8	140
System tie	150	1	180**
Substation	150	1	180**

*Based on prior load of 100% of rated and 30 °C ambient.

**This limit is based upon consideration of thermal aging and does not take into account the risk of insulation breakdown because of bubble formation above 140 °C. (See 2.2(1).)