



IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Immersed Transformers

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.169™-2023
(Revision of IEEE Std 1538™-2000)

STANDARDS

IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Immersed Transformers

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Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Provides guidance for determining the hottest-spot temperature in distribution and power transformers built in accordance with IEEE Std C57.12.00-2000. Describes the important criteria to be evaluated by a thermal model that can accurately predict the hottest-spot temperatures in a transformer. Provides guidance for performing temperature-rise tests with direct measurement of the hottest-spot temperatures and explains the importance of developing an accurate thermal model to properly locate the temperature sensors.

Keywords: distribution transformer, hottest-spot temperature, IEEE C57.169™, power transformers, temperature-rise test, thermal model

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Introduction

This introduction is not part of IEEE Std C57.169-2023, IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Immersed Transformers.

It is required by IEEE Std C57.12.00™ that the maximum (hottest-spot) winding temperature rise not exceed 80 °C. The hottest-spot temperature rise at rated load is a necessary parameter for determining the loading capability of all transformers. Since there was no approved test or calculation method to demonstrate compliance with the IEEE standard, an IEEE Working Group on Hottest-Spot Temperature Rise Determination in Liquid-Immersed Transformers was formed to develop this guide.

This guide provides information to determine the maximum (hottest-spot) winding temperature rise by calculation and testing. Modern computer technology permits calculation of maximum (hottest-spot) winding temperature. Most manufacturers use computers for their design calculations, and it is reasonable to incorporate a thermal subroutine into the programs that would calculate maximum (hottest-spot) winding temperature rises. Current personal computers have capabilities that were present only in mainframe computers decades ago. Fiber-optic temperature sensors now permit direct measurement of the temperature of a specific point. By prior analysis of the winding, the sensor can be placed to read the maximum winding temperature. For distribution transformers, thermal testing may be conducted using embedded thermocouples.

This guide applies to liquid-immersed power, network, and distribution transformers manufactured in accordance with IEEE Std C57.12.00. Although thermal gradients may be low in properly designed small (10–25 kVA) distribution transformers, the thermal gradients may not be low in the wide range of transformers classified as distribution transformers, which may extend in range to 5000 kVA.

This guide was originally published as IEEE Std 1538™-2000 and reaffirmed in 2011. Amendment 1, IEEE Std 1538a™-2015, was published because the state of the art had improved over the years since the last reaffirmation of this guide. This amendment added substantial detail and general recommendations for sensor location, based on the historical experiences of many fiber-optic measurements, providing sufficient detail for everyday use on common designs. Examples also provided illustration of proper sensor installation that was missing from the previously published guide.

This revision of the guide included a renumbering of the document into the IEEE C57 series of documents as IEEE Std C57.169, and includes the following changes:

- Incorporating the content from Amendment 1, IEEE Std 1538a-2015, into the main body of the guide
- Expanded discussion on direct measurement by fiber-optic detectors
- Expanded guidance within annex on fiber-optic probe installation
- Added discussion on the disc method for fiber-optic probe installation
- Added guidance on fiber-optic probe installation in shell-type transformers
- Removed definitions that are included in IEEE Std C57.12.80™
- General clarifying edits and updates

Acknowledgements

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IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Immersed Transformers

1. Overview

1.1 Scope

This document provides a guide for developing mathematical models and test procedures to determine the steady state maximum (hottest spot) and average winding temperature rise over ambient for liquid immersed distribution, power, network, and regulating transformers manufactured in accordance with IEEE Std C57.12.00.⁶

1.2 Purpose

This guide provides a basis for the transformer manufacturer and user to concur that a transformer meets the temperature requirements in C57.12.00. Those requirements state that the maximum winding temperature rise shall be determined by either direct measurement or calculations. This guide will describe the requirements for a manufacturer's test program or mathematical model to demonstrate compliance with those requirements.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

⁶ Information on normative references can be found in Clause 2

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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.

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.^{9,10}

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

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

3. Definitions

For the purposes of this document, the following terms and definitions apply. For other terms, the standard transformer terminology available in IEEE Std C57.12.80™ shall apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

flow direction: A method of designing the path of liquid flow in disc or helical windings by alternately blocking the vertical ducts inside and outside the winding to cause the liquid to flow in a zigzag pattern. This construction is used with either directed or non-directed flow transformers.

H-factor: A dimensionless number for predicting the maximum winding temperature rise over fluid due to increased eddy losses and other factors at the winding hottest-spot location.

maximum (hottest-spot) winding temperature: The maximum or hottest temperature of the current carrying components of a transformer winding and leads in contact with insulation or insulating fluid. The hottest-spot temperature is a naturally occurring phenomena due to the generation of losses and the heat-transfer phenomena. It is the highest temperature inside the transformer winding and leads and is greater than the measured average winding temperature. All transformers have a maximum (hottest-spot) winding temperature.

NOTE—In this guide the hottest-spot rise is not considered to be due to localized manufacturing defects. Defects that affect long term performance or cause the hottest-spot rise to exceed the limits set in IEEE Std C57.12.00-2015 should be corrected.¹²

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¹¹ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

maximum (hottest-spot) winding temperature rise: The arithmetic difference between maximum (hottest-spot) winding temperature and the ambient temperature.

oil: A shortened term for mineral oil that is a specially refined mineral-oil for use as an insulating liquid and coolant in transformers. For the purposes of this document, when terms such as “top oil rise” are used, “oil” should be considered synonymous with “fluid” since fluids other than mineral oil may be used. See IEEE Std C57.12.00.

prototype transformer: A transformer manufactured primarily to obtain engineering data or evaluate manufacturing or design feasibility. Prototypes may be preproduction units or units typical of current designs manufactured for test purposes to obtain data to comply with changes in industry standards or for other reasons.

4. Test methods

4.1 Direct measurement by fiber optic detectors¹³

4.1.1 Introduction

Fiber-optic temperature detectors are used to measure temperatures in distribution and power transformers. The main application of fiber-optic probes is the measurement of local temperatures in the windings, particularly at the expected hottest-spot temperature in the windings. The probes typically remain in the windings, and in some cases they are used for the measurement of temperatures under operating conditions.

There are fiber-optic probes on the market with embedded sensors in the conductors at certain intervals along their length. Such probes could measure the local temperatures along the length of the conductor. However, its use in power transformers, mainly in core-type, may not be very practical. One reason is that the probe must be embedded in a slot and placed next to a single conductor strand. This may create some complications, for example, at the transposition of parallel strands (in shell-type transformers this problem is at least more controlled, mainly if the fiber-optic is placed along the outermost turn of the coil). Another reason is that the current distribution is not completely balanced between parallel conductors, despite a proper transposition scheme. Furthermore, at the design stage it is not obvious which one of the parallel conductors carries the highest current. This makes selection of the proper conductor for probe installation uncertain, because probes would have to be installed in all the parallel conductors, which would be both expensive and time consuming. Consequently, point sensors are more likely to be used in most transformer applications.

When using point sensors, choosing the best installation locations is crucial to determining the hottest-spot temperature with reasonable accuracy. The term “reasonable accuracy” is used here to mean that the measured maximum temperature is close enough to the real hottest-spot temperature, such that it can be used as a reference for safe operation of the transformer and for the estimation of consumed transformer life. The probable location of the maximum (hottest-spot) winding temperature is usually determined by analysis of the eddy-loss distribution, the oil-flow distribution, and the heat-transfer characteristics of the winding. Unfortunately, large thermal scatter of measured results often overrides the theoretical predictions. Thus, a certain minimum number of probes are recommended. The following subclauses recommend the minimum number of probes and the recommended locations of probes in core-type transformers. It is then assumed that the windings per limb are of approximately equal length, are designed with axial or zig-zag oil circulation, that the load current is approximately sinusoidal, and that the

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