

C57.123™

IEEE Guide for Transformer Loss Measurement

IEEE Power Engineering Society

Sponsored by the
Transformers Committee



Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

5 December 2002

Print: SH95007
PDF: SS95007

Recognized as an
American National Standard (ANSI)

IEEE Std C57.123™-2002

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Approved 13 June 2002

IEEE-SA Standards Board

Abstract: Information and general recommendations of instrumentation, circuitry, calibration, and measurement techniques of no-load losses (excluding auxiliary losses), excitation current, and load losses of power and distribution transformers are provided. The guide is intended as a complement to the test code procedures given in Clause 8 and Clause 9 of IEEE Std C57.12.90-1999.

Keywords: calibration, load loss, no-load loss, testing, transformers

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Print: ISBN 0-7381-3309-4 SH95007
PDF: ISBN 0-7381-3310-8 SS95007

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Introduction

(This introduction is not part of IEEE Std C57.123-2002, IEEE Guide for Transformer Loss Measurement.)

During an earlier revision of Clause 8 and Clause 9 of IEEE Std C57.12.90, IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers, which describe the measurement of no load and load loss, respectively, it was realized that there was a need for a guide that would explain in more detail the accuracy requirements, test code procedures, various test methods available, methods to diagnose test anomalies, and the procedures for calibration and safety.

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Acknowledgment

A number of the Working Group members contributed to the text of this guide. Special acknowledgment is, however, due to Dr. Ed So and Messers Bill Henning, L. S. McCormick, Bertrand Poulin, and Ed teNyenhuis for providing specific sections of the text of this document. Finally, the chairman acknowledges that a large portion of the text on load-loss measurement (Clause 3 of the guide) was taken from the IEEE paper cited as reference [B7] of the guide and authored by Mr. Sam Mehta.

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IEEE Guide for Transformer Loss Measurement

1. Overview

This guide provides background information and general recommendations of instrumentation, circuitry, calibration and measurement techniques of no-load losses (excluding auxiliary losses), excitation current, and load losses of power and distribution transformers. The test codes, namely, IEEE Stds C57.12.90TM-1999, C57.12.91TM-2001, and the test code section of IEEE Std C57.15TM-1999, provide specifications and requirements for conducting these tests.¹ This guide has been written to provide supplemental information for each test. More technical details of the measuring instruments and techniques presented in this guide can be found in the document developed by So [B13].²

1.1 Scope

This guide applies to liquid-immersed-power and distribution transformers, dry-type transformers, and step-voltage regulators. Additionally, it applies to both single- and three-phase transformers.

1.2 Purpose

The purpose of the guide is to:

- a) Describe the basis and methodology by which the accuracy requirements of (Clause 8 and Clause 9) of IEEE Std C57.12.90-1999 for liquid-immersed transformers and IEEE Std C57.12.91-2001 for dry-type transformers can be achieved.
- b) Explain why the test code specifies certain procedures and limits.
- c) Explain advantages and disadvantages of different test methods where alternative methods are available.
- d) Explain practical limitations and valid means of overcoming them.
- e) Give theoretical basis for interpolation/extrapolation of tested data and valid limits.
- f) Explain test anomalies—how they result, what they mean, and how to handle them.
- g) Give procedures for calibration, certification, and traceability of measurement processes to reference standards.

¹Information on references can be found in Clause 2.

²The numbers in brackets correspond to those of the bibliography in Annex A.

- h) Discuss procedures for grounding, shielding, safety precautions, etc.
- i) Provide schematics and examples to clarify concepts and demonstrate methodologies.

2. References

This recommended practice shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

IEEE Std C57.12.00™-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.^{3,4}

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

IEEE Std C57.12.90-1999, Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.91-2001, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

IEEE Std C57.13™-1993, IEEE Standard Requirements for Instrument Transformers.

IEEE Std C57.15-1999, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage Regulators.

3. Transformer no-load losses

3.1 General

No-load losses (also referred to as excitation losses, core losses, and iron losses) are a very small part of the power rating of the transformer, usually less than 1%. However, these losses are essentially constant over the lifetime of the transformer (do not vary with load), and hence they generally represent a sizeable operating expense, especially if energy costs are high. Therefore, accurate measurements are essential in order to evaluate individual transformer performance accurately.

No-load losses are the losses in a transformer when it is energized but not supplying load. They include losses due to magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors. Load-tap-changing transformers may use preventive autotransformers, series transformers, or occasionally, both. In most designs the no-load losses of these auxiliary transformers add to the no-load losses of the main transformer when the tap changer is not in the neutral position. For example, the additional no-load losses of preventive autotransformers depend on whether the tap changer is bridging or non-bridging. For series transformers, the additional no-load losses depend on tap position. No-load losses are affected by a number of variables discussed in the following clause.

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⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

3.2 Parameters affecting magnitude of no-load losses

3.2.1 Induction

Losses in the core vary with the level of induction in the core (flux density), and thus the base no-load loss is established by the rated level of the design core flux density of the transformer.

3.2.2 Excitation voltage magnitude

Since the core flux density is a direct function of the magnitude of the excitation voltage, no-load losses are also a function of this voltage, for example, a 1% change in voltage causes a corresponding change in core losses generally in the 1%–3% range. The design and material used for the core determine the magnitude of the change in losses. It is, therefore, essential to have an accurate measurement of the magnitude of the excitation voltage.

3.2.3 Excitation voltage waveform

No-load losses are usually quoted and reported based on a sine-wave voltage excitation. Even with a sinusoidal source voltage, the non-linearity of the transformer core introduces significant harmonics into the excitation current and could result in distorted excitation voltage and flux waveforms. The magnitude of the voltage waveform distortion is usually determined by the output impedance of the voltage source and the magnitude and harmonics of the excitation current. The higher these parameters are, the greater will be the magnitude of the voltage waveform distortion. Figure 1 illustrates the supply transformer circuit at the no-load test.

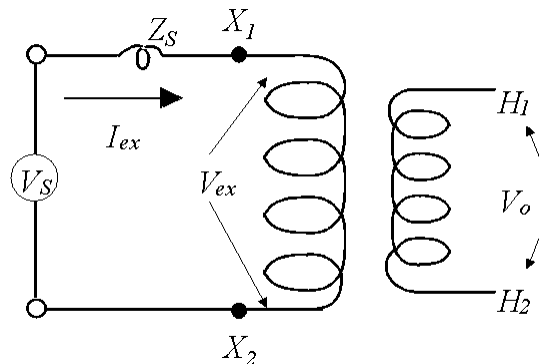


Figure 1—Transformer supply circuit at no-load test

where

- V_{ex} is the excitation voltage,
- V_S is the source voltage,
- V_O is the output voltage,
- I_{ex} is the excitation current,
- Z_S is the source impedance.

From Figure 1,

$$V_S = |V_S| \sin(\Omega t) \quad (1)$$

$$Z_{sn} \equiv R_s + j\omega X_s \quad (2)$$

$$I_{\text{ex}} = \sum I_{\text{ex}}^n \cos(n\Omega t + \phi_n) \quad (3)$$

$$V_{\text{ex}} = V_s - \sum Z_{\text{sn}} I_{\text{ex}}^n \quad (4)$$

where

- X_s is the source reactance,
- R_s is the source resistance,
- n is the order of harmonic,
- $\omega = 2\pi f$,
- ϕ_n = phase-angle for harmonic n .

Figure 2 shows a typical excitation current waveform. Assuming a source impedance of 10%, an excitation current equal to 2% of rated current, and a 50% fifth harmonic, the resultant excitation voltage will have approximately a 0.5% fifth harmonic.

Measurements will vary markedly with waveform. Peaked voltage waveforms (form factor greater than 1.11) result in lower losses than those of sine-wave voltage. Flat top waves, however, result in higher losses than those for the corresponding pure sine wave. It is, therefore, a requirement to accurately account for the effect of having a distorted waveform.

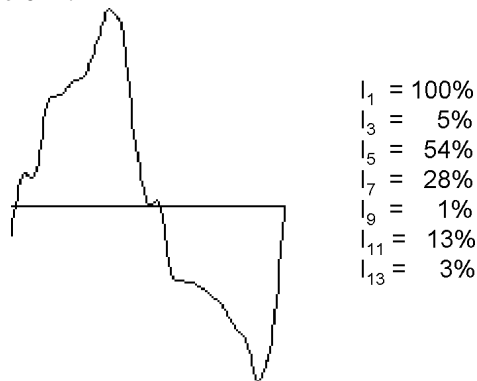


Figure 2—A typical excitation current waveform and harmonic content

3.2.4 Core configuration

Different core configurations; such as three-legged vs. five-legged cores or single-phase vs. three-phase cores, will yield different values of core loss (all other factors constant). This is caused by differences in the magnetic flux distribution in these different core configurations.

3.2.5 Core material

The magnetic properties of the core material itself, as well as the thickness and insulating coating of the individual laminations, have a direct effect on the magnitude of losses in a core. For example, higher grain-oriented grades of steel or thinner gauge laminations have lower iron losses than those of regular grain-oriented or thicker gauge steel grades, respectively. Amorphous metal cores generally have even lower magnitudes of core loss but operate at much lower flux densities because of a lower saturation level. Variability in material properties of the same grade of steel may give rise to noticeable differences in the core-loss performance of transformers of the same design. This effect is generally more noticeable in small transformers.

3.2.6 Frequency

Losses in the core have two main components: the hysteresis component and the eddy current component. The hysteresis loss component varies linearly with frequency. The eddy current component (containing both classical eddy losses and anomalous eddy losses) varies proportional to approximately the square of the frequency. The relative magnitudes of these two components are a function of the grade and thickness of steel used as well as the magnitude of the core flux density. Hence, these two parameters determine the magnitude of the effect of frequency on core losses. For examples, the 60 Hz to 50 Hz ratio of iron loss density at 1.5 T induction is typically 1.32 for 0.27 mm highly grain-oriented steel. This ratio is correspondingly equal to 1.26 for 0.23 mm regular-oriented steel at 1.75 T. Also, a frequency deviation of 0.5% corresponds to about 1% to 2% deviation in losses.

3.2.7 Workmanship

The quality of workmanship in slitting, cutting, annealing, and handling of the individual core laminations and the quality of the assembly of the core have a direct effect on the magnitude of core losses. Quality of joints in the core also affects the value of core loss to a certain extent but usually has a greater effect on the magnitude of the exciting current. These factors can partially explain why loss measurements on essentially duplicate units can differ by a few percent.

3.2.8 Core temperature

Core losses are affected to some degree by the temperature of the core at the time that losses are measured. Generally, core losses decrease with an increase in core temperature. This is due to a reduction of the eddy loss component of the core material iron loss caused by the higher resistivity of the material at higher temperatures. The calculation method to correct the measured values of core losses of distribution transformers to the reference temperature is given in 8.4 of IEEE Std C57.12.90-1999 and IEEE Std C57.12.91-2001. The magnitude of this effect is in reality a function of core design and core material. However, the effect is sufficiently small (about 1% for every 15 °C). In this case, using an average value of the correction factor would be satisfactory. The factor was chosen to be 0.065% per °C (0.00065 p.u. per °C). Its value was arrived at through consensus of the transformer industry and is based on typical values. Due to uncertainty in the actual value of the core temperature during operation, the reference temperature was chosen to be 20 °C for liquid-immersed transformers (per IEEE Std C57.12.00-2000). According to these standards, since core loss measurements on power transformers are typically made at, or near, room temperature, there is little need for applying temperature correction in this case.

3.2.9 Impulse tests

No-load loss measurements taken directly after impulse tests are usually slightly higher (typically 1% to 3%) than those taken beforehand. Higher magnitudes of increased no-load loss have been experienced in some cases. This phenomenon is not fully understood at the present time. Existing data, however, shows that this increase is seldom permanent and usually diminishes with time (several hours).

3.2.10 Core stabilization

When a transformer is energized for the purpose of no-load loss measurement, it may exhibit an initially high excitation current, a slightly higher core loss, and highly distorted voltage waveform. As the voltage is held constant, the current, loss, and distortion gradually decrease to the expected levels. The time period for this change to stabilize is typically a few seconds and may be longer for some transformer designs. The cause of this phenomenon is believed to be mainly due to the core residual magnetization phenomenon. To reduce the time to reach core stabilization, it is recommended that the core be excited first with higher flux density levels.