



IEEE Recommended Practice for Establishing Liquid-Filled and Dry- Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents

IEEE Power Engineering Society

Sponsored by the
Transformers Committee



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IEEE Recommended Practice for Establishing Liquid-Filled and Dry- Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents

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**Transformers Committee
of the
IEEE Power Engineering Society**

Approved 27 March 2008

IEEE-SA Standards Board

Abstract: This recommended practice provides calculation methods to conservatively evaluate the feasibility for an existing installed dry-type or liquid-filled transformer, to supply nonsinusoidal load currents as a portion of the total load. This recommended practice also provides necessary application information to assist in properly specifying a new transformer expected to carry a load, a portion of which is composed of nonsinusoidal load currents. A number of examples illustrating these methods and calculations are presented. Reference annexes provide a comparison of the document calculations to calculations found in other industry standards. Suggested temperature rise calculation methods are detailed for reference purposes.

Keywords: accuracy, current transformer, instrument transformer, primary winding, rated secondary voltage, routine tests, secondary winding, type tests, voltage transformer

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Introduction

(This introduction is not part of IEEE Std C57.110-2008, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.)

The widespread use of static rectification equipment in industrial loads on small and medium power dry-type and liquid-filled transformers has resulted in a dramatic increase in the harmonic content of the load current of these transformers. It has become common for the harmonic factor of the current to exceed 0.05 per-unit, which is the limit specified for “usual service conditions” in IEEE Std C57.12.00™ and IEEE Std C57.12.01™. The higher harmonic content in the load current of these transformers causes higher eddy current loss in the windings and the structural parts linked by the transformer leakage flux and, consequently, higher operating temperatures. Users of this document should also recognize that liquid-filled transformers may have different load limitations than dry-type transformers and that the harmonic loading practices should treat the two types of transformers differently when necessary.

This recommended practice provides guidance for the conservative loading of transformers carrying nonsinusoidal load currents such that overheating is avoided. The intent of this document is to provide simple methods of calculating these effects on either a new transformer or an existing transformer. More specifically, it is expected that this recommended practice would be used for the following situations:

- a) A new transformer required to carry some nonsinusoidal load currents, but **will not** be entirely devoted to a rectifier load.
- b) An existing transformer not originally specified for supplying nonsinusoidal load currents, but is now required to supply a load, a **portion** of which is nonsinusoidal.

Two methods are described in this recommended practice. The first method is intended to illustrate calculations by those with access to detailed information on loss density distribution within each of the transformer windings. The second method is less accurate and is intended for use by those with access to transformer-certified test report data only. It is anticipated that the first method will emphasize the information necessary to specify a new transformer and show how this information is used by transformer design engineers, whereas the second method will be employed primarily by users. This recommended practice will provide methods for conservatively evaluating the feasibility of applying nonsinusoidal load currents to existing transformers and will clarify the requirements for specifying new transformers to supply nonsinusoidal loads.

New transformers that are intended to supply loads with high harmonic content must be specified with a harmonic current distribution. The designer cannot “assume” nor can the user expect the designer to use “standard” or “typical” current distribution tables. If the harmonic content of the load is unknown, then both the user and the transformer designer are at risk and reasonable steps should be taken to ensure a conservative design for the application. Guidelines on how this information is used to develop proper transformer sizing is provided in this document, but appropriate calculations specific to the type of transformer design are the responsibility of the designer. Approximate calculation techniques that provide conservative results are provided for the typical user who has much less information than the transformer designer.

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Philip Hopkinson

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Dhiru Patel
Mahesh Sampat
Subhas Sarkar
John Sullivan

The following members of the balloting committee voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

William J. Ackerman
I. Antweiler
Adam Bagby
David Barnard
Wallace Binder
Thomas Bishop
Thomas Blackburn
Chris Brooks
Carl Bush
Thomas Callsen
Stephen Conrad
Tommy Cooper
Alan Darwin
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Donald Dunn
Gary Engmann
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1. Overview

~~Two methods are described in this recommended practice. The first is intended to illustrate calculations by those with access to detailed information on loss density distribution within each of the transformer windings. The second method is less accurate and is intended for use by those with access to transformer certified test report data only. It is anticipated that the first method will emphasize the information necessary to specify a new transformer and show how this information is used by transformer design engineers, while the second method will be employed primarily by users. This recommended practice will provide methods for conservatively evaluating the feasibility of applying nonsinusoidal load currents to existing transformers and will clarify the requirements for specifying new transformers to supply nonsinusoidal loads.~~

1.1 Scope

This recommended practice applies only to two winding transformers covered by IEEE Std C57.12.00, IEEE Std C57.12.01, and NEMA ST20.¹ It does not apply to rectifier transformers.

1.2 Purpose

The purpose of this document is to establish uniform methods for determining the capability of transformers to supply nonsinusoidal load currents of known characteristics.

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

2. Normative references

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

The following referenced documents are indispensable for the application of this document. 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 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.~~

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

IEEE Std C57.12.01TM, 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. ~~1993~~90TM, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating-Transformers

~~80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Trans-formers.~~

IEEE Std C57.12.91-~~1995~~TM, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

IEEE Std C57.91-~~1995~~TM, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

~~IEEE Std C57.12.90- and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers.~~

NEMA ST20-~~1992~~, Dry-Type Transformers for General Applications.²⁴

3. General considerations

3.1 Transformer losses

IEEE Std C57.12.90 and IEEE Std C57.12.91 categorize transformer losses as no-load loss (excitation loss), load loss (impedance loss), and total loss (the sum of no-load loss and load loss). Load loss is subdivided into I^2R loss and “stray loss.” Stray loss is determined by subtracting the I^2R loss (calculated from the measured resistance) from the measured load loss (impedance loss).

“Stray loss” can be defined as the loss due to stray electromagnetic flux in the windings, core, core clamps, magnetic shields, enclosure or tank walls, and so on. Thus, the stray loss is subdivided into winding stray loss and stray loss in components other than the windings (P_{OSL}). The winding stray loss includes winding conductor strand eddy-current loss and loss due to circulating currents between strands or parallel winding circuits. All of this loss may be considered to constitute winding eddy-current loss (P_{EC}). The total load loss can then be stated as follows in Equation (1):

$$P_{LL} = P + P_{EC} + P_{OSL} \quad \text{W (1)}$$

[where](#)

[P_{LL} is the load loss \(watts\)](#)

[P is the I²R loss portion of the load loss \(watts\)](#)

[P_{EC} is the winding eddy-current loss \(watts\)](#)

[P_{OSL} is the other stray loss \(watts\)](#)

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⁴ NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

3.1.1 Harmonic current effect on I²R loss

If the rms value of the load current is increased due to harmonic components, the I²R loss will be increased accordingly.

3.1.2 Harmonic current effect on [winding eddy-current loss](#)

Winding eddy-current loss (P_{EC}) in the [frequency range under consideration](#) (power frequency ~~spectrum~~ and [associated harmonics](#)) tends to be proportional to the square of the load current and [approximately proportional to](#) the square of frequency (see Crepaz [B5], Blume et al. [B3], Dwight [B7], as well as Bishop and Gilker [B2])⁵ It is this characteristic that can cause excessive winding loss and hence abnormal winding temperature rise [and hottest spot temperatures](#) in transformers supplying nonsinusoidal load currents.

3.1.3 Harmonic current effect on other stray loss

It is recognized that other stray loss (P_{OSL}) in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current. However, these losses will not increase at a rate proportional to the square of the frequency, as in the winding eddy losses. Studies by manufacturers and other researchers have shown that the eddy-current losses in bus bars, connections, and structural parts increase by a harmonic exponent factor of 0.8 or less. Therefore, [as a conservative estimate, an exponent of](#) 0.8 will be used throughout this document.⁴ ~~Temperature rise in these regions-~~ [The effects of these losses will also vary depending on the type of transformer. For example, the temperature rise in these non-winding parts will generally not](#) be very critical ~~than in the windings~~ for dry-type transformers. However, these losses must be properly accounted for in liquid-filled transformers, [since they contribute to additional heating of the insulating liquid and the hottest spots in the structural parts.](#)

3.1.4 DC components of load current

Harmonic load currents are frequently accompanied by a dc component in the load current. A dc component of load current will increase the transformer core loss slightly, but it will increase the magnetizing current and audible sound level more substantially. Relatively small dc components (up to the rms magnitude of the transformer excitation current at rated voltage) are expected to have no effect on the load carrying capability of a transformer determined by this recommended practice. Higher dc load current components may adversely affect transformer capability and should be avoided [or otherwise accounted for.](#)

3.1.5 Effect on top-oil rise

For liquid-filled transformers, the top oil rise (θ_{TO}); will increase as the total load losses increase due to harmonic loading. ~~Any increase in~~ [Unlike dry-type transformers, the](#) other stray loss (P_{OSL}) ~~will primarily~~ [must be considered, since these losses also](#) affect the top oil rise.

3.2 Transformer capability equivalent

The transformer capability established by following the procedures in this recommended practice is based on the following premises:

a) The transformer, except for the load harmonic current distribution, is presumed to be operated in accordance with “Usual Service Conditions” in IEEE Std C57.12.00 or IEEE Std C57.12.01.

⁵ The numbers in brackets correspond to those of the bibliography in Annex A.

⁶ See paragraph 2 of Annex D for additional information on this topic.

b) The transformer is presumed to be capable of supplying a load current of any harmonic content provided that the total load loss, the load loss in each winding, and the loss density in the region of the highest eddy-current loss do not exceed the levels for full load, rated frequency, and sine wave design conditions. It is also presumed that the limiting condition is the loss density in the region of highest winding eddy-current loss; hence, this is the basis used for establishing capability equivalency.⁵

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3.3 Basic data

In order to perform the calculations in this recommended practice, the characteristics of the nonsinusoidal load current must be defined either in terms of the magnitude of the fundamental frequency component or the magnitude of the total rms current. Each harmonic frequency component must also be defined from power system measurements. In addition, information on the magnitude of winding eddy-current loss density must be available.

3.4 Transformer per-unit losses

Since the greatest concern about a transformer operating under harmonic load conditions will be for overheating of the windings, it is convenient to consider loss density in the windings on a per-unit basis (base current is rated current and base loss density is the I^2R loss density at rated current). Thus, Equation (1) applied to rated load conditions can be rewritten on a per-unit basis as follows in Equation

$$(P_{LL-R}(\text{pu}) = 1 + P_{EC-R}(\text{pu}) + P_{OSL-R}(\text{pu}) \text{ pu}) \quad (2)$$

where

$P_{LL-R}(\text{pu})$ is the per-unit load loss under rated conditions

$P_{EC-R}(\text{pu})$ is the per-unit winding eddy current loss under rated conditions

$P_{OSL-R}(\text{pu})$ is the per-unit other stray loss under rated conditions;

~~2-for additional information on this topic.⁵The simple methods of calculation of transformer capability equivalent given in this document assume that currents at all harmonic frequencies generate loss in a constant path resistance. In fact, skin effect becomes more pronounced as frequency increases and eddy current loss is smaller than predicted. Thus, the methods presented document become increasingly conservative~~

Given the eddy-current loss under rated conditions for a transformer winding or portion of a winding, (P_{EC-R}), the eddy-current loss due to any defined nonsinusoidal load current can be expressed as follows in ~~this~~ Equation (3):

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I_R} \right)^2 h^2 \text{ W}$$

where

P_{EC} is the winding eddy-current loss (watts)

P_{EC-R} is the winding eddy-current loss under rated conditions (watts)

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at the higher harmonic included in the calculation, particularly those above the 19th. “ h ” (amperes)

I_R is the rms fundamental current under rated frequency and rated load conditions (amperes)

⁷ The simple methods of calculation of transformer capability equivalent given in this document neglect the skin effect, which becomes more pronounced at frequencies in the upper portion of the frequency range under consideration.

The I^2R loss at rated load is one per-unit (by definition). For nonsinusoidal load currents, the equation for the rms current in per-unit form (base current is rated current), will be as follows in Equation (4):

$$I(\text{pu}) = \sqrt{\sum_{h=1}^{h=h_{\max}} I_h(\text{pu})^2} \text{ pu}$$

where

$I(\text{pu})$ is the per-unit rms load current

h is the harmonic order

h_{max} is the highest significant harmonic number

$I_h(\text{pu})$ is the per-unit rms current at harmonic “ h ”

Equation (3) can also be written in per-unit form (base current is the rated current and base loss density is the I^2R loss density at rated current) as follows in Equation (5):

$$P_{EC}(\text{pu}) = P_{EC-R}(\text{pu}) \sum_{h=1}^{h=h_{\max}} I_h(\text{pu})^2 h^2 \text{ pu}$$

where

$P_{EC}(\text{pu})$ is the per-unit winding eddy-current loss

$P_{EC-R}(\text{pu})$ is the per-unit winding eddy-current loss under rated conditions

h is the harmonic order

$h_{\max}$ is the highest significant harmonic number

$I_h(\text{pu})$ is the per-unit rms current at harmonic “ h ”

3.5 Transformer losses at measured currents

Equation (2) through Equation (5) assumes that the measured application currents are taken at the rated currents of the transformer. Since this is seldom encountered in the field, a new term is needed to describe the winding eddy losses at the measured current and the power frequency; P_{EC-O} . Three assumptions in addition to the basic premises of the Transformer Capability Equivalent are necessary to clarify the use of this term:

- The eddy losses are approximately proportional to the square of the frequency. This assumption will cause any subsequent equations to be accurate for small conductors and low harmonics, ~~with errors on the high side,~~ providing a conservative calculation. for a combination of larger conductors and higher harmonics.
- The eddy losses are a function of the current in the conductors. Any equation for loss can then be expressed in terms of the rms load current I .
- Superposition of eddy losses will apply, which will permit the direct addition of eddy losses due to the various harmonics.

Equation (3) and Equation (5) may now be written more generally as in Equation (6):

$$P_{EC} = P_{EC-O} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I} \right)^2 h^2 \text{ W}$$

where

P_{EC} is the winding eddy-current loss (watts)

P_{EC-O} is the winding eddy-current loss at the measured current and the power frequency (watts)

h is the harmonic order

$h_{\max}$ is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

I is the rms load current (amperes)

By removing the rms current term, I from the summation, we now have Equation (7):

$$P_{EC} = P_{EC-O} \times \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^2}{I^2} \text{ W}$$

where

P_{EC} is the winding eddy-current loss (watts)

P_{EC-O} is the winding eddy-current loss at the measured current and the power frequency (watts)

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

I is the rms load current (amperes)

The rms value of the nonsinusoidal load current is then given by Equation (8):

[where](#)

[I is the rms load current \(amperes\)](#)

[h is the harmonic order](#)

[h_{max} is the highest significant harmonic number](#)

[I_h is the rms current at harmonic “h” \(amperes\)](#)

The rms current term, I may be expressed in terms of the component frequencies as follows in Equation (9):

$$I = \sqrt{\sum_{h=1}^{h=h_{max}} I_h^2} \text{ A}$$

where

P_{EC} is the winding eddy-current loss (watts)

P_{EC-O} is the winding eddy-current loss at the measured current and the power frequency (watts)

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

3.6 Harmonic loss factor⁸ for winding eddy currents

It is convenient to define a single number that may be used to determine the capabilities of a transformer in supplying power to a load. F_{HL} is a proportionality factor applied to the winding eddy losses, which represents the effective rms heating as a result of the harmonic load current. F_{HL} is the ratio of the total winding eddy current losses due to the harmonics, (P_{EC}), to the winding eddy current losses at the power frequency, [when](#) no harmonic currents exist (P_{EC-O}). This definition in equation form is as follows in Equation (10):

$$F_{HL} = \frac{P_{EC}}{P_{EC-O}} = \frac{\sum_{h=1}^{h=h_{max}} I_h^2}{\sum_{h=1}^{h=h_{max}} I_h^2}$$

where

F_{HL} is the harmonic loss factor for winding eddy currents

P_{EC} is the winding eddy-current loss (watts)

P_{EC-O} is the winding eddy-current loss at the measured current and the power frequency (watts)

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

Equation (10) permits F_{HL} to be calculated in terms of the actual rms values of the harmonic currents. Harmonic analyzers permit calculations to be made in terms of the harmonics normalized to the total rms current or to the first or fundamental harmonic. Equation (10) may be adapted to these situations by dividing the numerator and denominator by either I , the rms load current, or by I_1 , the rms fundamental load current, ~~or by I , the total rms current I_L .~~ These terms may now be applied to Equation (10) term by term, resulting in Equation (11) and Equation (12):

~~Note that the quantity~~

~~may be directly read on a meter, by~~

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I} \right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I} \right]^2}$$

~~passing the computation procedure.~~

where

F_{HL} is the harmonic loss factor for winding eddy currents

h is the harmonic order

h_{max} is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

I is the rms load current (amperes)

⁸ The harmonic loss factor is similar but not identical to the K-factor referenced in other standards. For a comparison of the Harmonic loss factor with the K-factor definition referenced in UL standards, see Annex B.

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1} \right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1} \right]^2}$$

where

F_{HL} is the harmonic loss factor for winding eddy currents

h is the harmonic order

$h_{\max}$ is the highest significant harmonic number

I_h is the rms current at harmonic “ h ” (amperes)

I_l is the rms fundamental load current (amperes)

Note that the quantity I_h / I_l may be directly read on a meter, bypassing the computation procedure.

In either case, F_{HL} remains the same value, since it is a function of the harmonic current distribution and is independent of the relative magnitude. Two examples may be used to clarify these definitions. In both examples a nonsinusoidal load current of 1804 A rms will be used as the rated current. The load may be described by the harmonic distribution in Table 1, normalized to the rms load current of 1804 A

Table 1— Example of a harmonic distribution normalized to the rms load current

h	I_h	$\frac{I_h}{I}$
1	1764	0.978
5	309	0.17
7	308.5195	0.1711
11	194.9794	0.108044
13	79.39505	0.044028
17	50.52271	0.028015
19	27.06177	0.0150098
49	17.68	0.0098

The calculation is tabulated in Table