

IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents

Sponsor

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Abstract: Methods are developed to conservatively evaluate the feasibility of supplying additional nonsinusoidal load currents from an existing installed dry-type or liquid-filled transformer, as a portion of the total load. Clarification of the necessary application information is provided 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 make a comparison of the document calculations to calculations found in other industry standards and suggested temperature rise methods are detailed for reference purposes.

Keywords: current, eddy-current losses, harmonic current, harmonic load losses, harmonic loss factor, harmonics, K-factor, load currents, nonsinusoidal, transformer

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Introduction

(This introduction is not part of IEEE Std C57-110-1998, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.)

The widespread use of static rectification equipment in industrial loads on small and medium power transformers has resulted in a dramatic increase in the harmonic content of the load current for this equipment. It is quite 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 C57.12.00-1993 and IEEE Std C57.12.01-1998. It is also well known that higher harmonic content in the current causes higher eddy current loss in winding conductors and structural parts linked by the transformer leakage flux field and, consequently, higher operating temperatures.

For a number of years this recommended practice has provided guidance in conservative loading practices so that overloading could be avoided for transformers carrying nonsinusoidal load currents. However, users have communicated the need for certain clarifications to the IEEE Transformers Committee. A working group was formed to respond to this need and has revised the subject recommended practice. ***Precise determination of the extra eddy-current loss produced by harmonic currents is a complex subject that is highly dependent on the design and construction of the transformer and may involve sophisticated computer analysis.*** The intent of the original document will be followed and such treatment ***will not*** be given. The intent of this document is to present simple uniform methods of describing a load so that either a new transformer may be adequately described to the supplier or an existing transformer may be evaluated for conservative loading. More specifically, it is expected that this standard would be used for the following situations:

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

The increased use of electronic loads such as computers and adjustable-speed-drive motors in light industrial, commercial, and residential loads has created a need to apply the harmonic loading practices to liquid-filled distribution transformers below the small and medium power ratings. In extending the practices down to distribution ratings, it is recognized that the existing methods may be extremely conservative for smaller ratings and that less extensive derating methods may apply.

Users of this revised 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 transformer types differently when necessary.

Transformers which 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.

In revising this recommended practice, the document was updated to current IEEE style formats and restructured to permit easier use. New sections were added to more clearly address new transformer specification and liquid-filled transformers. The quantity f was deleted and F_{HL} and F_{HL-STR} , Harmonic Loss Factors for winding eddy currents and for other stray losses were defined to simplify and expand the formulas. Additional examples were also added to clarify the formulas, to include liquid-filled transformers, and to emphasize the importance of the required load information and its impact on the transformer size. Annexes were added for clarification, one of which compares the Underwriters Laboratories, Inc. (UL) K-Factor definition

and the IEEE Std C57.110-1998 Harmonic Loss Factor definition. The other annex presents information on procedures for performing a temperature rise test.

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IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents

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 C57.12.00-1993, IEEE Std C57.12.01-1998, and NEMA ST20-1992. 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.

2. 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.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.¹

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 C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers.

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

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

NEMA ST20-1992, Dry-Type Transformers for General Applications.²

3. Definitions

All definitions are in accordance with IEEE Std 100-1996, or are in accordance with the standards quoted in the text.

3.1 Letter symbols

F_{HL}	Harmonic loss factor for winding eddy currents
F_{HL-STR}	Harmonic loss factor for other stray losses
h	Harmonic order
h_{max}	Highest significant harmonic number ($h_{max} = 25$)
I	RMS load current (amperes)
I_1	RMS fundamental load current (amperes)
I_h	RMS current at harmonic “ h ” (amperes)
I_{max}	Maximum permissible rms nonsinusoidal load current (amperes)
I_R	RMS fundamental current under rated frequency and rated load conditions (amperes)
I_{1-R}	High voltage (HV) rms fundamental line current under rated frequency and rated load conditions (amperes)
I_{2-R}	Low voltage (LV) rms fundamental line current under rated frequency and rated load conditions (amperes)
I_T	RMS test current (amperes)
I_{1-T}	HV rms test current (amperes)
I_{2-T}	LV rms test current (amperes)
P_{EC}	Winding eddy-current loss (watts)
P_{EC-R}	Winding eddy-current loss under rated conditions (watts)
P_{EC-O}	Winding eddy-current losses at the measured current and the power frequency (watts)
P	I^2R loss portion of the load loss (watts)
P_{DC}	Total calculated I^2R losses at ambient temperature (watts)
P_{2-DC}	LV calculated I^2R losses at ambient temperature (watts)

¹IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

²NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://www.global.ihs.com/>).

P_{AC}	Measured impedance losses at ambient temperature (watts)
P_{LL}	Load loss (watts)
P_{LL-R}	Load loss under rated conditions (watts)
P_{NL}	No load loss (watts)
P_{OSL}	Other stray loss (watts)
P_{OSL-R}	Other stray loss under rated conditions (watts)
P_{TSL-R}	Total stray loss under rated conditions (watts)
R	DC resistance (ohms)
R_1	DC resistance measured between two HV terminals (ohms)
R_2	DC resistance measured between two LV terminals (ohms)
θ_g	Hottest-spot conductor rise over top-oil temperature ($^{\circ}\text{C}$)
θ_{g-R}	Hottest-spot conductor rise over top-oil temperature under rated conditions ($^{\circ}\text{C}$)
θ_{g1}	Hottest-spot HV conductor rise over top-oil temperature ($^{\circ}\text{C}$)
θ_{g1-R}	Hottest-spot HV conductor rise over top-oil temperature under rated conditions ($^{\circ}\text{C}$)
θ_{TO}	Top-oil-rise over ambient temperature ($^{\circ}\text{C}$)
θ_{TO-R}	Top-oil-rise over ambient temperature under rated conditions ($^{\circ}\text{C}$)
(pu)	This symbol modifier may be added to the listed symbols to represent a per-unit value of that quantity. Current quantities are referred to the rated rms load current I_R , and loss quantities are referred to the rated load I^2R loss density. e.g.: $I_h(\text{pu})$ and $P_{EC-R}(\text{pu})$.

4. General considerations

4.1 Transformer losses

IEEE Std C57.12.90-1993 and IEEE Std C57.12.91-1995 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, etc. 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

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

4.1.1 Harmonic current effect on I^2R loss

If the rms value of the load current is increased due to harmonic components, the I^2R loss will be increased accordingly.

4.1.2 Harmonic current effect on P_{EC}

Winding eddy-current loss (P_{EC}) in the power frequency spectrum tends to be proportional to the square of the load current and the square of frequency (see Crepez [B5], Blume et al., [B3], Dwight [B6], and Bishop and Gilker [B2])³. It is this characteristic that can cause excessive winding loss and hence abnormal winding temperature rise in transformers supplying nonsinusoidal load currents.

³The numbers in brackets preceded by the letter B correspond to those of the bibliography in Annex A.

4.1.3 Harmonic current effect on P_{OSL}

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, 0.8 will be used throughout this document.⁴ Temperature rise in these regions will be less critical than in the windings for dry-type transformers. However, these losses must be properly accounted for in liquid filled transformers.

4.1.4 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 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.

4.1.5 Effect on top oil rise

For liquid-filled transformers, the top oil rise (θ_{TO}), will increase as the total load losses increase with harmonic loading. Any increase in other stray loss (P_{OSL}) will primarily affect the top oil rise.

4.2 Transformer capability equivalent

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

- 1) The transformer, except for the load harmonic current distribution, is presumed to be operated in accordance with "Usual Service Conditions" in IEEE Std C57.12.00-1993 or IEEE Std C57.12.01-1998.
- 2) 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, sine wave design conditions. It is further 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

4.3 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.

⁴See Annex D, paragraph 2 for additional information on this topic.

⁵The simple methods of calculation of transformer capability equivalent given in this document assume that eddy 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 in this document become increasingly conservative at the higher harmonic included in the calculation, particularly those above the 19th.

4.4 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:

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

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

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I_R} \right)^2 h^2 \quad \text{watts} \quad (3)$$

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:

$$I(\text{pu}) = \sqrt{\sum_{h=1}^{h=h_{\max}} I_h(\text{pu})^2} \quad \text{pu} \quad (4)$$

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

$$P_{EC}(\text{pu}) = P_{EC-R}(\text{pu}) \sum_{h=1}^{h=h_{\max}} I_h(\text{pu})^2 h^2 \quad \text{pu} \quad (5)$$

4.5 Transformer losses at measured currents

Equations (2) through (5) assume 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:

- 1) 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, for a combination of larger conductors and higher harmonics.
- 2) 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 .
- 3) Superposition of eddy losses will apply, which will permit the direct addition of eddy losses due to the various harmonics.

Equations (3) and (5) may now be written more generally in the following equation:

$$P_{EC} = P_{EC-O} \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I} \right)^2 h^2 \quad \text{watts} \quad (6)$$

By removing the rms current term, I from the summation, the equation becomes

$$P_{EC} = P_{EC-O} \times \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^2}{I^2} \quad \text{watts} \quad (7)$$

The rms value of the nonsinusoidal load current is then given by

$$I = \sqrt{\sum_{h=1}^{h=h_{\max}} I_h^2} \quad \text{amperes} \quad (8)$$

The rms current term, I may be expressed in terms of the component frequencies

$$P_{EC} = P_{EC-O} \times \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{\max}} I_h^2} \quad \text{watts} \quad (9)$$

4.6 Harmonic Loss Factor⁶ for winding eddy currents

It is convenient to define a single number which 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 eddy-current losses due to the harmonics, (P_{EC}), to the eddy-current losses at the power frequency, as if no harmonic currents existed, (P_{EC-O}). This definition in equation form is

$$F_{HL} = \frac{P_{EC}}{P_{EC-O}} = \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{\max}} I_h^2} \quad (10)$$

Equation (10) permits F_{HL} to be calculated in terms of the actual rms values of the harmonic currents. Various measuring devices 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_1 , the fundamental harmonic current, or by I , the total rms current I_1 . These terms may now be applied to Equation (10) term by term, resulting in Equations (11) and (12).

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{\max}} \left[\frac{I_h}{I_1} \right]^2 h^2}{\sum_{h=1}^{h=h_{\max}} \left[\frac{I_h}{I_1} \right]^2} \quad (11)$$

Note that the quantity $\frac{I_h}{I_1}$ may be directly read on a meter, by passing the computation procedure.

⁶The 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.

$$F_{\text{HL}} = \frac{\sum_{h=1}^{h=h_{\text{max}}} \left[\frac{I_h}{I} \right]^2 h^2}{\sum_{h=1}^{h=h_{\text{max}}} \left[\frac{I_h}{I} \right]^2} \quad (12)$$

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 following harmonic distribution, normalized to the rms load current of 1804 A:

h	I_h	$\frac{I_h}{I}$
1	1764	0.978
5	308.5	0.171
7	194.9	0.108
11	79.39	0.044
13	50.52	0.028
17	27.06	0.015
19	17.68	0.0098

The calculation is tabulated as follows:

h	$\frac{I_h}{I}$	$\left(\frac{I_h}{I} \right)^2$	h^2	$\left(\frac{I_h}{I} \right)^2 h^2$
1	0.978	0.9570	1	0.957
5	0.171	0.0290	25	0.731
7	0.108	0.0120	49	0.571
11	0.044	0.0020	121	0.234
13	0.028	0.00078	169	0.133
17	0.015	0.00023	289	0.065
19	0.0098	0.00010	361	0.035
Σ	—	1.000	—	2.726