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(Revision of IEEE Std C57.110-1986)

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

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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.

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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)

[1]IEEE 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/).

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

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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 (°C)
$\theta_{g–R}$	Hottest-spot conductor rise over top-oil temperature under rated conditions (°C)
θ_{g1}	Hottest-spot HV conductor rise over top-oil temperature (°C)
$\theta_{g1–R}$	Hottest-spot HV conductor rise over top-oil temperature under rated conditions (°C)
θ_{TO}	Top-oil-rise over ambient temperature (°C)
$\theta_{TO–R}$	Top-oil-rise over ambient temperature under rated conditions (°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(pu) and $P_{EC–R}$(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

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

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 Crepaz [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.

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

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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.

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

[5]The 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.

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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:

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

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

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

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:

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

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):

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

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:

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

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

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

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

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

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

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

4.6 Harmonic Loss Factor[6] 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

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

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).

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

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

[6]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.

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

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

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The summation of the third column, $(I_h/I)^2$, is equal to 1.000 and represents the rated rms load on a per-unit basis. The Harmonic Loss Factor for this harmonic distribution is

$$F_{HL} = \frac{2.726}{1.000} = 2.726$$

This same loading example may also be described in terms of the harmonic currents normalized to the harmonic current of the fundamental frequency, as follows:

h	I_h	$\frac{I_h}{I_1}$
1	1764	1.000
5	308.5	0.175
7	194.9	0.110
11	79.39	0.045
13	50.52	0.029
17	27.06	0.015
19	17.68	0.010

Note that the values of the harmonic current, I_h, are the same in both examples, but the normalized values are different since these values are normalized to the harmonic current of the fundamental frequency. The calculation is tabulated as follows:

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2 h^2$
1	1.000	1.0000	1	1.0000
5	0.175	0.0306	25	0.7643
7	0.110	0.0122	49	0.5975
11	0.045	0.0020	121	0.2449
13	0.029	0.0008	169	0.1385
17	0.015	0.0002	289	0.0680
19	0.010	0.0001	361	0.0362
Σ	—	1.0459	—	2.8494

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Whether the individual harmonic currents are normalized to the rms load current I, or to the fundamental load current I_1, the value of harmonic loss factor is the same:

$$F_{HL} = \frac{2.726}{1.000} = \frac{2.8494}{1.0459} = 2.726$$

4.7 Harmonic Loss Factor for other stray losses

Although the heating due to other stray losses is generally not a consideration for dry-type transformers, it can have a substantial effect on liquid-filled transformers. A relationship similar to the Harmonic Loss Factor for winding eddy losses exists for these other stray losses in a transformer, and may be developed in a similar manner. However, the losses due to bus bar connections, structural parts, tank, etc. are proportional to the square of the load current and the harmonic frequency to the 0.8 power, as stated in 4.1.3. This may be expressed in a form similar to Equation (3).

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_R}\right)^2 h^{0.8} \quad \text{watts} \tag{13}$$

The equations corresponding to the Harmonic Loss Factor, normalized to the fundamental current and normalized to the rms current respectively are

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_1}\right]^2} \tag{14}$$

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2} \tag{15}$$

Using the harmonic distribution from the last example of the previous section, the calculation is tabulated for the normalized fundamental current base, as follows:

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	$h^{0.8}$	$\left(\frac{I_h}{I_1}\right)^2 h^{0.8}$
1	1.000	1.0000	1.0000	1.00000
5	0.175	0.0306	3.6239	0.11098
7	0.110	0.0122	4.7433	0.05739
11	0.045	0.0020	6.8095	0.01379
13	0.029	0.0008	7.7831	0.00655
17	0.015	0.0002	9.6463	0.00217
19	0.010	0.0001	10.5439	0.00105
Σ	—	1.0459	—	1.1919

$$F_{HR-STR} = \frac{1.1919}{1.0459} = 1.140$$

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5. Design considerations for new transformer specification

5.1 Harmonic current filtering

When it is practical, the user may install filters on the secondary line to reduce some of the harmonic load currents supplied to the transformer. If one of the harmonic frequencies is close to the resonant frequency resulting from the filtering circuit, current amplification at this frequency may occur.

5.2 Impact on the neutral

When the harmonic current frequencies include harmonic orders having multiples of three (3, 6, 9, etc.), zero sequence currents flow in the neutral. Over-sizing of this neutral may be required. In those circumstances, a common practice is to double the neutral ampacity.

5.3 Power factor correction equipment

Power factor correction equipment is frequently installed to decrease utility costs. Care should be taken when this is done, since current amplification at certain frequencies due to resonance in the circuit can be quite high. In addition, the inductance which is reduced in the circuit generally allows higher harmonic currents to exist in the system. Harmonic heating effects from these conditions may be damaging to transformers and other equipment. The additional losses produced may also increase utility costs due to increased wattage requirements, even though the load power factor was improved.

5.4 Electrostatic ground shields

Electrostatic ground shields are frequently specified between the primary and secondary windings. The presence of electrostatic ground shields tends to reduce capacitive coupling between the windings. This reduces the coupling of transients between the two windings. Line disturbances produced by converter equipment connected to the transformer secondary will be reduced, but will not be eliminated on the primary side of the transformer. The shields are not intended to reduce harmonic currents, but by virtue of their magnetic coupling to windings carrying such currents, additional heating losses are induced. The electrostatic shields are a supplement but not necessarily a replacement for harmonic current filtering. Therefore, filtering may still be needed to achieve the desired power quality.

The electrostatic shields also serve as protection to the secondary side of the transformer from transients that may be impressed on the high-voltage winding. This is especially important for transformers with ungrounded secondaries. Transients on the high-voltage side of a transformer can dramatically increase the surge voltage seen on an ungrounded secondary winding from what may have been expected for a grounded winding. This may damage transformer windings and parts or equipment connected on the secondary side of the transformer. The presence of an electrostatic ground shield between the primary and secondary windings reduces the magnitude of the transient coupled to the secondary windings.

5.5 Design consideration outside the windings

Harmonic currents can substantially increase the stray losses in structural parts outside of the windings. Additional clearances, the use of non-magnetic materials in place of mild steel, the break up of potential circulation current paths, and the use of shielding materials should all be considered as ways to reduce the effects of harmonic current heating in structural parts. These other stray losses, P_{OSL}, must be included in the losses used to determine top oil rise, $\Delta\theta_{TO}$, under harmonic loading conditions.

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5.6 Harmonic spectrum analysis

It is preferred that the harmonic spectrum to which the transformer will be subjected be specified to the transformer manufacturer at the time of quotation. An accurate analysis for proper sizing of the transformer can only be made by evaluating the specific harmonic spectrum. If the spectrum cannot be supplied, then the user's calculation or estimate of F_{HL} should be specified. However, the unit will likely be conservatively sized to compensate for the lack of specific loading information. The specifying engineer must supply this loading information, since the transformer manufacturer cannot assume values with no real knowledge of the system to which the transformer will be applied. For liquid-filled transformers, stray losses other than the winding eddy losses contribute to heating of the oil. Since F_{HL-STR} is calculated with a different exponent, the value of this factor must also be supplied by the specifying engineer if no spectrum analysis is provided. The harmonic spectrum supplied should be identified as to whether it is measured on the primary or secondary side of the transformer. If the harmonic spectrum is provided in per-unit form, then the fundamental should be defined at the rated frequency of the transformer specified.

5.7 Design consideration in the windings

Since harmonic currents can substantially increase the eddy-current losses in the windings, this increase of losses must be considered in the temperature rise calculation when a new transformer is specified. For each winding, the per-unit eddy-current losses in the region of highest loss density can be defined for rated frequency operation at rated current by the transformer manufacturer in terms of Equation (2), with $P_{OSL-R}(\text{pu})$ equal to zero (since there is no other stray loss in the windings by definition). The per-unit loss density in these regions of highest eddy-current loss can then be recalculated for the defined nonsinusoidal load current by combining Equations (2),(5),(8), and (11).

$$P_{LL}(\text{pu}) = I(\text{pu})^2 \times (1 + F_{HL} \times P_{EC-R}(\text{pu})) \qquad \text{pu} \tag{16}$$

To adjust the per-unit loss density in the individual windings, the effect of F_{HL} must be known on each winding. Thus the low voltage winding, with its larger conductor cross section may start with a lower loss density and a lower temperature rise, but may increase more than the high-voltage winding and exhibit the hottest spot in the transformer for harmonic loads. That is to say, there is one value of F_{HL} for the load, but the effects on different transformers and different windings within the same transformer can be different. For liquid-filled transformers, heating of the oil by stray losses other than the eddy losses also affects the temperature rise of the windings.

In these mentioned regions, considering the per-unit loss density obtained by Equation (16) with a nonsinusoidal load current of 1 (pu) rms magnitude, limits of temperature and temperature rise given in IEEE Std C57.12.00-1993 and IEEE Std C57.12.01-1998 must be met.

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6. Recommended procedures for evaluating the load capability of existing transformers[7]

6.1 Transformer capability equivalent calculation using design eddy-current loss data

6.1.1 Typical calculations for dry-type transformers

The per-unit eddy-current loss in the region of highest loss density can be defined for rated frequency operation at rated current by the transformer manufacturer in terms of Equation (2), with $P_{OSL–R}$(pu) equal to zero (since there is no other stray loss in the windings by definition).

The per-unit value of nonsinusoidal load current that will make the result of the Equation (16) calculation equal to the design value of loss density in the highest loss region for rated frequency and for rated current operation is given by Equation (17). This assumes that the normal life of the unit will be maintained. However, it is permissible to overload a unit with a resulting loss of life, and there are loading guides for this purpose.

$$I_{\max}(\text{pu})\sqrt{\frac{P_{\text{LL}-\text{R}}(\text{pu})}{1+F_{\text{HL}}\times P_{\text{EC}-\text{R}}(\text{pu})}} \quad \text{pu} \tag{17}$$

Two examples illustrate the use of these formulas. Given a nonsinusoidal load current with the following harmonic distribution, determine the maximum load current that can be continuously drawn (under standard conditions) from an IEEE standard transformer having a rated full load current of 1200 A and whose winding eddy-current loss under rated conditions ($P_{EC–R}$) at the point of maximum loss density is 15% of the local I^2R loss.

h	$\frac{I_h}{I_1}$
1	1.000
5	0.233
7	0.108
—	—
11	0.042
13	0.027
17	0.013
19	0.008

[7]The user is cautioned that local and national electrical codes should be consulted before any installed unit is officially "derated," such as changing the nameplate. Some units may not be "derated" without violating these codes.

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The maximum per-unit local loss density under rated conditions, P_{LL-R}(pu) is then 1.15 pu. Equations (16) and (17) require values for $I_h(pu)^2$, h^2, and $I_h(pu)^2h^2$. These can be calculated and tabulated as follows:

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2 h^2$
1	1.000	1.000	1	1.0000
5	0.233	0.0543	25	1.3572
7	0.108	0.0117	49	0.5715
11	0.042	0.0018	121	0.2134
13	0.027	0.0007	169	0.1232
17	0.013	0.0002	289	0.0488
19	0.008	0.0001	361	0.0231
Σ	—	1.0687	—	3.3374

From Equation (16), the local loss density for the nonsinusoidal load current is:

$$P_{LL}\ (pu) = 1.069 \times (1 + 3.123 \times 0.15) = 1.569\ pu$$

and the maximum permissible nonsinusoidal load current with the given harmonic composition, from Equation (17), is:

$$I_{max}(pu) = \sqrt{\frac{1.15}{1 + 3.123 \times 0.15}} = 0.885\ pu$$

or

$$I_{max} = 0.885 \times 1200 = 1062\ A$$

Thus, with the given nonsinusoidal load current harmonic composition, the transformer capability is approximately 89% of its sinusoidal load current capability.

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The following example of a nonsinusoidal load current has a strong third harmonic content with the following harmonic distribution:

h	$\frac{I_h}{I}$	h	$\frac{I_h}{I}$
1	0.969	11	0.1100
3	0.367	13	0.0709
5	0.354	15	0.0259
7	0.102	17	0.0568
9	0.0279	19	0.0472

Determine the maximum load current that can be continuously drawn (under standard conditions) from a 225 kVA standard transformer having a rated full load secondary current of 624.5 A and whose average winding eddy-current loss under rated conditions (P_{EC-R}) at the point of maximum loss density is 11.7% of the local I^2R loss.

The maximum per-unit local loss density under rated conditions, P_{LL-R}(pu) is then 1.117 pu. Equations (16) and (17) require values for $I_h(pu)^2$, h^2, and $I_h(pu)^2h^2$. These can be calculated and 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	0.9690	0.93896	1	0.9390
3	0.3670	0.13469	9	1.2122
5	0.3540	0.12532	25	3.1329
7	0.1020	0.01040	49	0.5098
9	0.0279	0.00078	81	0.0631
11	0.1100	0.01210	121	1.4641
13	0.0709	0.00503	169	0.8495
15	0.0259	0.00067	225	0.1509
17	0.0568	0.00323	289	0.9324
19	0.0472	0.00223	361	0.8043
Σ		1.2334		10.06

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From Equation (16), the local loss density for the nonsinusoidal load current is

$$P_{LL}\ (\text{pu}) = 1.233 \times (1.\ 8.156 \times 0.117) = 2.410\ \text{pu}$$

and the maximum permissible nonsinusoidal load current with the given harmonic composition, from Equation (17), is

$$I_{max}(\text{pu}) = \sqrt{\frac{1.117}{1 + 8.156 \times 0.117}} = 0.756\ \text{pu}$$

or

$$I_{max} = 0.756 \times 624.5 = 472.1\ \text{A}$$

Thus, with the given nonsinusoidal load current harmonic composition, the transformer capability is approximately 76% of its sinusoidal load current capability.

6.1.2 Typical calculations for liquid-filled transformers

The calculations for liquid-filled transformers are similar to the dry-type, except the effect of all stray losses must be addressed. As indicated by equations in IEEE Std C57.91-1995, for self-cooled ONAN[8] mode, the top oil rise is proportional to the total losses to the 0.8 exponent and may be estimated for the harmonic losses, based on rated load and losses as shown below.

$$\theta_{TO} = \theta_{TO-R} \times \left(\frac{P_{LL} + P_{NL}}{P_{LL-R} + P_{NL}}\right)^{0.8} \quad °\text{C} \tag{18}$$

where

$$P_{LL} = P + F_{HL} \times P_{EC} + F_{HL-STR} \times P_{OSL} \quad \text{watts} \tag{19}$$

The winding hot spot conductor rise is also proportional to the load losses to the 0.8 exponent and may be calculated as follows:

$$\theta_{g} = \theta_{g-R} \times \left(\frac{P_{LL}(\text{pu})}{P_{LL-R}(\text{pu})}\right)^{0.8} \quad °\text{C} \tag{20}$$

This may then be written as

$$\theta_{g} = \theta_{g-R} \times \left(\frac{1 + F_{HL} \times P_{EC-R}(\text{pu})}{1 + P_{EC-R}(\text{pu})}\right)^{0.8} \quad °\text{C} \tag{21}$$

[8]Formerly designated as OA.

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As an example, a 65 °C average winding rise, 80 °C hottest spot rise oil-filled transformer was designed for a specified harmonic current content. After installation, the actual harmonic currents were measured and the current spectrum was supplied to the manufacturer with a request to check the temperature rises. At rated load and 60 Hz, the tested losses were

No load	4072 W
I^2R	27 821 W
Stray and eddy loss	4 060 W
Total loss	35 953 W

The measured temperature rises above ambient were

HV average rise	48.1 °C
LV average rise	47.6 °C
Top-oil rise	47.2 °C
Hot spot conductor rise	55.3 °C

The harmonic distribution was determined at a load, which was approximately 100% of the magnitude of the fundamental current. The distribution, normalized to the fundamental, was supplied as follows:

h	$\frac{I_h}{I_1}$	h	$\frac{I_h}{I_1}$
1	1.00	13	0.0512
3	0.351	15	0.0425
5	0.169	17	0.0402
7	0.121	19	0.0387
9	0.0915	23	0.0321
11	0.0712	25	0.0286

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The calculations to determine the Harmonic Loss Factors for the winding eddy losses and the other stray losses are tabulated below.

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2$	$\left(\frac{I_h}{I}\right)^2$	$\left(\frac{I_h}{I_1}\right)^2 h^{0.8}$
1	1.000	1.000000	1	1.000000	1.000000	1.000000
3	0.351	0.123201	9	1.108809	2.408225	0.296696
5	0.169	0.028561	25	0.714025	3.623898	0.103502
7	0.121	0.014641	49	0.717409	4.743276	0.069446
9	0.0915	0.008372	81	0.678152	5.799546	0.048555
11	0.0712	0.005069	121	0.613402	6.809483	0.034520
13	0.0512	0.002621	169	0.443023	7.783137	0.020403
15	0.0425	0.001806	225	0.406406	8.727161	0.015763
17	0.0402	0.001616	289	0.467036	9.646264	0.015589
19	0.0387	0.001498	361	0.540666	10.54394	0.015792
23	0.0321	0.001030	529	0.545087	12.28520	0.012659
25	0.0286	0.000818	625	0.511225	13.13264	0.010742
Σ	—	1.189234	—	7.745241	—	1.643667

The third column summation results in an rms current value of 1.09 pu. The fifth column summation results in a Harmonic Loss Factor for the winding eddy losses of 6.51, and the seventh column summation results in a Harmonic Loss Factor for the other stray losses of 1.38.

An engineering analysis indicated the division of the eddy and other stray losses to be

Eddy loss	316 W
Other stray loss	3744 W
Total stray loss	4060 W

In order to determine the top-oil rise, the total losses must be corrected to reflect the higher rms current above the rated current and also the effects of the harmonic content.

$$P_{LL}(\text{pu}) = P_{LL\text{–}R}(\text{pu}) \times (1.09)^2$$

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Equation (19) is then tabulated as follows:

Type of loss	Rated losses (watts)	Load losses (watts)	Harmonic multiplier	Corrected losses
No-load	4072	4072		4072
I^2R	27 821	33 034		33 034
Winding eddy	316	375	6.52	2446
Other stray	3744	4446	1.38	6153
Total losses	35 953	41 927		45 687

The top-oil rise for the specified loading conditions may now be calculated by Equation (18):

$$\theta_{TO} = 47.2 \times \left(\frac{45687}{35953}\right)^{0.8} = 57.2\ ^\circ\text{C}$$

The maximum per-unit eddy loss occurred in the high-voltage winding and was calculated to be an average of 2% of the ohmic loss. Assuming that the maximum eddy loss at the hot spot region to be four times the average eddy loss would give an eddy loss of 8% of the ohmic loss density at the hot spot location. The hot spot conductor rise over top-oil temperature can be calculated by Equation (21).

$$\theta_g = (55.3 - 47.2) \times \left(\frac{1 + 6.52 \times 0.08}{1 + 0.08} \times 1.189\right)^{0.8} = 12.2\ ^\circ\text{C}$$

The hot spot conductor rise over ambient then becomes

$57.2 + 12.2 = 69.4\ ^\circ\text{C}$

6.2 Transformer capability equivalent calculation using data available from certified test report

In order to make the calculation with limited data, certain assumptions have been made that are considered to be conservative. These assumptions may be modified based on guidance from the manufacturer for a particular transformer.

1) The certified test report includes all data listed in the appendixes to IEEE Std C57.12.90-1993 or IEEE Std C57.12.91-1995.

2) A portion of the stray loss, determined by the multipliers below, is assumed to be winding eddy-current loss. This is a conservative assumption and should not be followed if better data can be cited.

   a) 67% of the total stray loss is assumed to be winding eddy losses for dry-type transformers.

   b) 33% of the total stray loss is assumed to be winding eddy losses for oil-filled transformers.

3) The I^2R loss is assumed to be uniformly distributed in each winding.

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4) The division of eddy-current loss between the windings is assumed to be as follows:[9]

   a) 60% in the inner winding and 40% in the outer winding for all transformers having a maximum self-cooled current rating of less than 1000 A (regardless of turns ratio).

   b) 60% in the inner winding and 40% in the outer winding for all transformers having a turns ratio of 4:1 or less.

   c) 70% in the inner winding and 30% in the outer winding for all transformers having a turns ratio greater than 4:1 and also having one or more windings with a maximum self cooled current rating greater than 1000 A.

5) The eddy-current loss distribution within each winding is assumed to be nonuniform.[10] The maximum eddy-current loss density is assumed to be in the region of the winding hottest-spot and is assumed to be 400% of the average eddy-current loss density for that winding. Finite element analyses and empirical data indicate that smaller ratings may show a uniform distribution of eddy-current loss (Hwang [B11]).

As established in test codes IEEE Std C57.12.90-1993 and IEEE Std C57.12.91-1995, the stray loss component of the load loss is calculated by subtracting the I^2R loss of the transformer from the measured load loss. Therefore

$$P_{TSL-R} = P_{LL-R} - K \times [(I_{1-R})^2 \times R_1 + (I_{2-R})^2 \times R_2] \quad \text{watts}^{11} \tag{22}$$

where

K = 1.0 for single-phase transformers
= 1.5 for three-phase transformers

By assumption 2) of this section, a portion of the stray loss is taken to be eddy-current loss. For dry-type transformers, the winding-eddy loss is assumed to be:

$$P_{EC-R} = P_{TSL-R} \times 0.67 \tag{23}$$

For oil-filled transformers, the winding eddy loss is assumed to be

$$P_{EC-R} = P_{TSL-R} \times 0.33 \quad \text{watts} \tag{24}$$

The other stray losses are then calculated as follows:

$$P_{OSL-R} = P_{TSL-R} - P_{EC-R} \quad \text{watts} \tag{25}$$

---

[9] A high percentage of the leakage flux flowing axially in and between the windings is attracted radially inward at the ends of the windings because there is a lower reluctance return path through the core leg than through the unit permeability space outside the windings. As a result, the highest magnitude of the radial component of leakage flux density (and highest eddy loss) occurs in the end regions of the inner winding. In the absence of other information, the inner winding may be assumed to be the low-voltage winding. The eddy-loss distribution assumptions 4) and 5) are very conservative.

[10] See footnote 8.

[11] NOTE—Many test reports for three-phase transformers show the resistance of three phases in series. In these cases values for R_1 and R_2 may be calculated as follows:

Delta winding: R_1 or R_2 = 2/9 of three-phase resistance
Wye winding: R_1 or R_2 = 2/3 of three-phase resistance

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The low-voltage (inner) winding eddy-current loss can be calculated from the value of $P_{EC–R}$ determined from Equations (23) or (24) as either 0.6 $P_{EC–R}$ watts or 0.7 $P_{EC–R}$ watts, depending on the transformer turns ratio and current rating. Since by assumption 3) above, the I^2R loss is assumed to be uniformly distributed within the winding, and by assumption 5), the maximum eddy-current loss density is assumed to be 400% of the average value, the low voltage winding eddy-current loss in per unit of that winding's I^2R loss will be either

$$P_{EC-R}(\text{pu}) = \frac{2.4 \times P_{EC-R}}{K \times (I_{2-R})^2 \times R_2} \text{ pu} \tag{26}$$

or

$$P_{EC-R}(\text{pu}) = \frac{2.8 \times P_{EC-R}}{K \times (I_{2-R})^2 \times R_2} \text{ pu} \tag{27}$$

The winding eddy losses for the outer or HV winding may be calculated in a similar manner. For liquid-filled transformers, Equation (21) becomes

$$\theta_{g1} = \theta_{g1-R} \times \left(\frac{1 + 2.4 \times F_{HL} \times P_{EC-R}(\text{pu})}{1 + 2.4 \times P_{EC-R}(\text{pu})}\right)^{0.8} \quad °\text{C} \tag{28}$$

or

$$\theta_{g1} = \theta_{g1-R} \times \left(\frac{1 + 2.8 \times F_{HL} \times P_{EC-R}(\text{pu})}{1 + 2.8 \times P_{EC-R}(\text{pu})}\right)^{0.8} \quad °\text{C} \tag{29}$$

6.2.1 Typical calculations for dry-type transformers

Given a nonsinusoidal load current with the following harmonic distribution:

h	$\frac{I_h}{I_1}$	h	$\frac{I_h}{I_1}$
1	1.00	8	0.010
2	0.044	9	0.018
3	0.092	10	0.015
4	0.022	11	0.046
5	0.412	12	0.010
6	0.018	13	0.048
7	0.199	—	—

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Determine the maximum load current that can be continuously drawn (under standard conditions) from an IEEE Std C57.12.01-1998 dry-type transformer with the following characteristics taken from the certified test report.

— High-voltage winding
  13 800 V Delta
  Resistance = 2.0679 Ω @ 100 °C*
— Low-voltage winding
  480 V Wye
  Resistance = 0.000589 Ω @ 100 °C*
— Rated capacity
  2500 kVA, three-phase, 80 °C rise
  Type AA
— Load losses at 100 °C = 15 723 W
  (*Resistances are the sum of the three phases in series.)

— Values for R_1 and R_2 can be determined using the note in 6.2:
  $R_1 = 0.4595\ \Omega$ $R_2 = 0.000393\ \Omega$
— Values for $I_{1\text{-}R}$ and $I_{2\text{-}R}$ calculated from kVA and voltage ratings are as follows:
  $I_{1–R} = 104.6$ A $I_{2–R} = 3007$ A
— The total stray loss can be calculated from Equation (22) as follows:
  $P_{TSL–R} = 15\,723 – 1.5 \times (104.6^2 \times 0.4595 + 3007^2 \times 0.000393)$
  $P_{TSL–R} = 15\,723 – 1.5 \times (5027 + 3554)$
  $P_{TSL–R} = 15\,723 – 12\,872 = 2851$ W
— The winding eddy loss is then calculated by assumption 2) in 6.2 and by Equation (23).
  $P_{EC–R} = 2851 \times 0.67 = 1910$ W

Since the transformer turns ratio exceeds 4:1 and the secondary current exceeds 1000 A, the low-voltage winding eddy-current loss is 0.7 times $P_{EC–R}$ and Max $P_{EC–R}$ can be calculated from Equation (27) as follows:

$$\text{Max } P_{EC-R}(\text{pu}) = \frac{2.8 \times 1910}{1.5 \times 3554} = 1.003 \text{ pu}$$

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As in the previous example, values for $I_h(pu)^2$, h^2, and $I_h(pu)^2h^2$ are required for the calculation of $P_{LL}(pu)$ from Equation (16). These are calculated and tabulated as follows:

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2 h^2$
1	1.000	1.000	1	1.0000
2	0.044	0.00194	4	0.00776
3	0.092	0.00846	9	0.07614
4	0.022	0.00048	16	0.00765
5	0.412	0.16974	25	4.24350
6	0.018	0.00032	36	0.01152
7	0.199	0.03960	49	1.9404
8	0.010	0.00010	64	0.0064
9	0.018	0.00032	81	0.02592
10	0.015	0.00023	100	0.02300
11	0.046	0.00212	121	0.25652
12	0.010	0.00010	144	0.01440
13	0.048	0.00230	169	0.38870
Σ	—	1.226	—	8.002

Applying the 3rd column summation in Equation (8) gives an rms value of the nonsinusoidal load current of 1.107. From Equation (16), the local loss density produced by the nonsinusoidal load current in the region of highest eddy-current loss is

$$P_{LL}\,(pu) = 1.226 \times (1 + 1.003 \times 6.528) = 9.253\ pu$$

Thus, the rms value of the maximum permissible nonsinusoidal load current with the given harmonic composition, from Equation (17), is

$$I_{max}(pu) = \sqrt{\frac{2.003}{1 + 6.528 \times 1.003}} = 0.515\ A$$

or

$$I_{max} = 0.515 \times 3007 = 1549\ A$$

In this case, the transformer capability with the given nonsinusoidal load current harmonic composition is approximately 52% of its sinusoidal load current capability.

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6.2.2 Typical calculations for liquid-filled transformers

The next example illustrates the corrected temperature rise calculations for a liquid-filled transformer, meeting IEEE Std C57.12.00-1993, with the following characteristics taken from the certified test report.

- High-voltage winding
  34 500 V Delta
  Resistance = 18.207 Ω @ 75 °C*
- Low-voltage winding
  2400 V Wye
  Resistance = 0.02491Ω @ 75 °C*
- Rated capacity
  2500 kVA, three-phase, 55 °C average winding rise, 65 °C hottest spot rise
  Type OA
- No-load losses = 5100 W
- Load losses at 75 °C = 21941 W
- (*Resistances are the sum of the three phases in series.)

- Values for R_1 and R_2 can be determined using the note in 6.2:
  $R_1 = 4.046\ \Omega \quad R_2 = 0.01661\ \Omega$
- Values for $I_{1–R}$ and $I_{2–R}$ calculated from kVA and voltage ratings are as follows:
  $I_{1–R} = 41.8\ \text{A} \quad I_{2–R} = 601.4\ \text{A}$
- The total stray loss can be calculated from Equation (22) as follows:
  $P_{TSL–R} = 21\,941 – 1.5 \times (41.8^2 \times 4.046 + 601.4^2 \times 0.01661)$
  $P_{TSL–R} = 21\,941 – 1.5 \times (7069 + 6008)$
  $P_{TSL–R} = 21\,941 – 19\,615 = 2326\ \text{W}$
- The winding eddy loss is then calculated by assumption 2) in 6.2 and by Equation (24).
  $P_{EC–R} = 2326 \times 0.33 = 767\ \text{W}$
- By Equation (25), the other stray losses are:
  $P_{OSL–R} = 2326 – 767 = 1559\ \text{W}$

The data may be tabulated as follows:

No load	5100 W
I^2R	19 615 W
Stray and eddy loss	2326 W
Total loss	27 041 W

The assumed temperature rises above ambient are

HV and LV average rise	55 °C
Top-oil rise	55 °C
Hot spot conductor rise	65 °C

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The harmonic distribution was determined at a load which was approximately 75% of the magnitude of the fundamental current. The distribution, normalized to the fundamental, was supplied as follows:

h	$\frac{I_h}{I_1}$	h	$\frac{I_h}{I_1}$
1	1.00	11	0.0712
3	0.453	13	0.0512
5	0.267	15	0.0425
7	0.186	17	0.0402
9	0.0915	19	0.0387

The calculations to determine the Harmonic Loss Factors for the winding eddy losses and the other stray losses are tabulated below.

h	$\frac{I_h}{I_1}$	$\left(\frac{I_h}{I_1}\right)^2$	h^2	$\left(\frac{I_h}{I_1}\right)^2 h^2$	$h^{0.8}$	$\left(\frac{I_h}{I_1}\right)^2 h^{0.8}$
1	1.000	1.000000	1	1.000000	1.000000	1.000000
3	0.453	0.205209	9	1.846881	2.408225	0.494189
5	0.267	0.071289	25	1.782225	3.623898	0.258344
7	0.186	0.034596	49	1.695204	4.743276	0.164098
9	0.0915	0.008372	81	0.678152	5.799546	0.048555
11	0.0712	0.005069	121	0.613402	6.809483	0.034520
13	0.0512	0.002621	169	0.443023	7.783137	0.020403
15	0.0425	0.001806	225	0.406406	8.727161	0.015763
17	0.0402	0.001616	289	0.467036	9.646264	0.015589
19	0.0387	0.001498	361	0.540666	10.54394	0.015792
Σ	—	1.332077	—	9.472996	—	2.067254

The third column summation results in an rms current value of 1.15 pu. The fifth column summation results in a Harmonic Loss Factor for the winding eddy losses of 7.11, and the seventh column summation results in a Harmonic Loss Factor for the other stray losses of 1.55.

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The division of the eddy and other stray losses is tabulated as follows:

Eddy loss	767 W
Other stray loss	1559 W
Total stray loss	2326 W

In order to determine the top-oil rise, the total losses must be corrected to reflect the lower rms current below the rated current and also the effects of the harmonic content. The rms current corrected for the 75% load results in the following multiplier to determine losses at the specified load conditions:

$$P_{LL}\ (\text{pu}) = 1.15^2 \times 0.75^2 = 0.744$$

Equation (19) is tabulated as follows:

Type of loss	Rated losses (watts)	Rated losses (watts)	Harmonic multiplier	Corrected losses
No-load	5100	5100		5100
I^2R	19 615	14 592		14 592
Winding eddy	767	571	7.11	4060
Other stray	1559	1160	1.55	1798
Total losses	27 041	21 423		25 550

The top-oil rise may now be calculated by Equation (18).

$$\theta_{TO} = 55 \times \left(\frac{25550}{27041}\right)^{0.8} = 52.6\ ^\circ\text{C}$$

The rated inner or LV winding losses can be calculated as follows:

$$I_{2\text{–R}}^2\, R = 1.5 \times 601.4^2 \times 0.01661 = 9011\ \text{W}$$

The losses under the specified load conditions are

$$I_2^2\, R = 9011 \times (1.15 \times 0.75)^2 = 6704\ \text{W}$$

By assumption 4) in 6.2, since the currents are less than 1000 A, it is assumed that 60% of the winding eddy losses are in the LV winding. The maximum eddy loss at the hot spot region is assumed to be four times the average eddy loss. The hot spot conductor rise over top-oil temperature can be calculated by Equation (20) and (26), using watts rather than per unit values.

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$$\theta_g = (65 - 55) \times \left(\frac{6704 + 4060 \times 2.4}{9011 + 767 \times 2.4}\right)^{0.8} = 10 \times \left(\frac{6704 + 9744}{9011 + 1841}\right)^{0.8} = 13.9\ ^\circ\text{C}$$

The hot spot conductor rise over ambient then becomes

52.6 + 13.9 = 66.5 °C

NOTE—This temperature rise exceeds the limit of the rated 65 °C hottest spot rise.

6.3 Neutral bus capability for nonsinusoidal load currents that include third harmonic components

The presence of third harmonic components in the nonsinusoidal load current composition can introduce zero-sequence currents into the neutral bus of a wye-connected transformer. Excessive heating of the neutral bus may occur when the cumulative magnitude of the zero-sequence current for all phases exceeds the neutral bus capability.

When third harmonic components are found to be present in the nonsinusoidal load current for wye connected transformers, a measurement of the neutral bus ampacity is recommended to determine the magnitude of the zero-sequence current. The transformer manufacturer may then be consulted to determine the capability of the neutral bus to carry the zero-sequence current.

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Annex A

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Annex B

(informative)

Comparison of UL K-factor definition and IEEE Std C57.110-1998 Harmonic Loss Factor definition

B.1 UL Definition of K-Factor

The definition for the K-factor rating for dry-type transformers is given in UL 1561-1994 and UL 1562-1994. Per Paragraph 7B.1 added to UL 1562 on May 12, 1992, UL defines K-factor as follows:[12]

1) "K-FACTOR—A rating optionally applied to a transformer indicating its suitability for use with loads that draw nonsinusoidal currents."

2) "*The K–factor equals* $\sum_{h=1}^{\infty} I_{\mathrm{h}}(\mathrm{pu})^2 h^2$

where

$I_{\mathrm{h}}(\mathrm{pu})$ = the rms current at harmonic "h" (per unit of rated rms load current);
h = the harmonic order."

3) "K-factor rated transformers have not been evaluated for use with harmonic loads where the rms current of any singular harmonic greater than the tenth harmonic is greater than 1/h of the fundamental rms current."

B.2 Relationship between K-factor and Harmonic Loss Factor

The UL definition of K-factor is based on using the transformer rated current in the calculation of per-unit current in the above equation. Substituting the rated current into the UL equation for the K-factor gives

$$K\text{-}factor = \sum_{h=1}^{\infty} \left[\frac{I_{\mathrm{h}}}{I_R}\right]^2 h^2 = \frac{1}{I_R^2} \sum_{h=1}^{\infty} I_{\mathrm{h}}{}^2 h^2 \qquad \text{(B-1)}$$

where

I_{R} = rated rms load current of transformer.

The Harmonic Loss Factor, as defined by IEEE Std C57.110-1998, is given by Equation (11) as follows:

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

[12]The following standards should be consulted for a complete description of UL requirements for K-factor rated dry-type transformers:
1. UL 1561-1994, Dry-Type General Purpose and Power Transformers.
2. UL 1562-1994, Transformers, Distribution, Dry-Type—Over 600 Volts.

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I_1 is a constant and may be moved in front of the summation sign and eliminated as shown in Equation (B-2).

$$F_{HL} = \frac{\frac{1}{I_1^2}\sum_{h=1}^{h=h_{max}} I_h^2 h^2}{\frac{1}{I_1^2}\sum_{h=1}^{h=h_{max}} I_h^2} = \frac{\sum_{h=1}^{h=h_{max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{max}} I_h^2} \quad \text{(B-2)}$$

Then rearranging Equation (B-2) gives

$$\sum_{h=1}^{h=h_{max}} I_h^2 h^2 = F_{HL} \sum_{h=1}^{h=h_{max}} I_h^2 \quad \text{(B-3)}$$

substituting the above in Equation (B-1) gives

$$K\text{-}factor = \left[\frac{\sum_{h=1}^{h=h_{max}} I_h^2}{I_R^2}\right] F_{HL} \quad \text{(B-4)}$$

The above equation gives the relationship of the Harmonic Loss Factor to the UL K-factor. The Harmonic Loss Factor is a function of the harmonic current distribution and is independent of the relative magnitude. The UL K-factor is dependent on both the magnitude and distribution of the harmonic current. For measurements of harmonic currents in existing installations the numerical value of the K-factor is different from the numerical value of the Harmonic Loss Factor. For a set of harmonic load current measurements the calculation of the UL K-factor is dependent on the transformer rated secondary current. For a new transformer with harmonic currents specified as per unit of the rated transformer secondary current the K-factor and Harmonic Loss Factor have the same numerical values. The numerical value of the K-factor equals the numerical value of the Harmonic Loss Factor only when the square root of the sum of the harmonic currents squared equals the rated secondary current of the transformer.

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B.3 Example calculations

Assume an existing installation with a 2500 kVA, 480 V three-phase dry-type transformer. Harmonic load current measurements were made as given in the table below. The K-factor is calculated as shown below.

I_R = 3007.1 A

h	h^2	I_h	$\frac{I_h}{I_R}$	$\left(\frac{I_h}{I_R}\right)^2$	$\left(\frac{I_h}{I_R}\right)^2 h^2$
1	1	1764	0.5866117	0.3441133	0.3441133
5	25	308.5	0.1025905	0.0105248	0.2631205
7	49	194.9	0.0648133	0.0042008	0.2058373
11	121	79.39	0.0264009	0.0006970	0.0843376
13	169	50.52	0.0168002	0.0002822	0.0476999
17	289	27.06	0.0089987	0.0000810	0.0234023
19	361	17.68	0.0058794	0.0000346	0.0124789
				Σ = K-factor =	0.9810

Similar calculations may be made for other transformer kVA ratings applied to the same set of harmonic load current measurements as shown above. For transformers rated less than 1500 kVA, the rms value of the harmonic load currents exceeds the rated transformer current. The results are summarized below for the same set of harmonic current measurements. The Harmonic Loss Factor is calculated as shown in 4.6.

KVA	I_R-rated current	K-factor	Harmonic Loss Factor F_{HL}
1500	1804.0	2.726	2.726
2000	2405.7	1.533	2.726
2500	3007.1	0.981	2.726

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Annex C

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Temperature rise testing procedures

C.1 Proposed method of performing a rigorous temperature rise test[13]

The temperature rise test with harmonic secondary load should be made under normal service conditions of the equipment, with the unit fully assembled and with its normal means of cooling. Liquid filled transformers will be filled to their proper liquid level. If transformers are equipped with thermal indicators, bushing-type current transformers, or the like, such devices should be assembled with the transformer.

The conditions under which the temperature limits apply are stated in either IEEE Std C57.12.01-1998 or IEEE Std C57.12.00-1993 as applicable for dry or liquid-filled transformer types. Note that special temperature rise limits may apply for certain high harmonic load test conditions; these limits should be agreed on by the manufacturer and the purchaser representative for specific applications only. Unless otherwise specified, all transformers should be tested in the combination of connections and taps that gives rise to the highest winding temperature rise in each test condition.

C.1.1 Standard definitions and procedures

Refer to either IEEE Std C57.12.91-1995 or IEEE Std C57.12.90-1993 for the standard definitions and procedures as appropriate to the particular design.

C.1.2 Transformer components temperature measurement

Due to the rapid spatial variation of the temperature within, and on the surface of, the various transformer components, thermocouples in intimate contact are the preferred method of measuring temperature. The need for several thermocouples within the coils and core of the transformer will necessitate these being attached during the manufacture of the test specimen, due regard being made of the dielectric circumstances in the design and routing of the thermocouples. Detailed drawings of the location and method of attachment of all thermocouples should be included in the test report. Temperatures should be recorded at regular intervals, not exceeding 30 min.

C.1.2.1 Winding temperature measurement

Thermocouples should be attached directly to the winding turns, at locations determined from electromagnetic/thermal studies as having the highest expected temperature rises. Thermocouples should be fitted on three-phase transformers to at least the center phase and one outside phase winding group, and to both the primary and secondary coils on all transformers. The average temperature rise of the windings should be determined by the resistance method.

[13]This test procedure is provided as a reference for a rigorous test of the transformer temperature rise. However, transformer manufacturers do not have the capability to test to this method, particularly as the size of the unit increases. Furthermore, at the time this document was developed, there have been reports of only a few small units having been tested according to this method. Nevertheless, the procedure provides a comparison to the more practical, but much less accurate alternatives listed later in this annex. It is also hoped that by documenting this procedure, an accurate reference may be provided by which more practical and more accurate methods of simulated load temperature rise testing might be developed.

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C.1.2.2 Core temperature measurement

Thermocouples should be attached directly to the core surfaces at locations determined from electromagnetic/thermal studies as having the highest expected temperature rises. These are expected to be inside the corners of the winding window in close proximity to the coils whose harmonic field strengths are concentrated. The thermocouples should maintain firm contact with the surface and be thermally insulated from the surrounding medium.

C.1.2.3 Structural and enclosure temperature measurement

Thermocouples or thermometers should be placed to record the maximum exterior enclosure temperatures and the temperatures of internal structural parts susceptible to high temperature rises. In particular, iron or alloy parts in close proximity to terminals carrying large currents or to the magnetic core, should be monitored for their temperature rise.

C.1.2.4 Liquid temperature measurement

In liquid-filled transformers the top liquid temperature should be measured by a thermocouple or suitable thermometer immersed approximately 50 mm (2 in) below the top liquid surface. The average liquid temperature should be taken to be equal to the top liquid temperature minus half the difference in temperature of the moving liquid at the top and the bottom of the cooling means. Where the bottom liquid temperature cannot be measured directly, the temperature difference may be taken to be the difference between the surface temperature of the liquid inlet and outlet.

C.1.3 Electrical loading conditions

The intent of the temperature rise test under harmonically loaded conditions is to simulate, as closely as practical, the actual in-service conditions. In so doing, the specific current frequency spectra should be specified for each loading condition to be tested, and these should be standardized or agreed by a specific customer. The primary winding is to be energized directly from a sinusoidal source, with the secondary winding loaded by a system capable of drawing the necessary harmonic currents.

C.1.3.1 Primary winding source characteristics

The primary winding should be directly connected to a power source whose open circuit voltage is sinusoidal, and equal to the rated voltage of the winding in its test tap connection. The impedance of the primary winding sources should be related to the rating of the transformer to be tested by the following procedure.

Select the standard rating of a circuit breaker or switch whose rating is sufficient to supply the test transformer, the standard ratings being chosen from those approved by NEMA. Denote these selected values as V_{rated} and I_{rated}, and hence calculate the rated circuit load impedance as

$$Z_{\text{L}} = \frac{V_{\text{rated}}}{\sqrt{3} \times I_{\text{rated}}} \text{ for a three-phase circuit}$$

The primary winding source impedance should then lie within the range of 10–20% by magnitude of the rated circuit load impedance, and the ratio of the source reactance to resistance should then lie between the values of 5 and 7.

Example: 3.4 MVA, three-phase transformer, 3.8 kV primary voltage
Rated primary current = 516.6 A
Standard NEMA switch rating, 4.76 kV, 600 A
Z_{L} = 4.58 Ω/phase

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Minimum source impedance = 0.458 Ω/phase consisting of
complex impedance components in the range 0.090 + j 0.449
to 0.065 + j 0.453 Ω/phase.

Maximum source impedance = 0.916 Ω/phase consisting of
complex impedance components in the range 0.180 + j 0.898
to 0.130 + j 0.906 Ω/phase.

In the case of a single phase transformer, the equivalent calculation should be carried out to the same principles.

The primary winding source should not be modified in its natural harmonic or regulation response, so as to artificially affect the natural high frequency regulation of the source by the test transformer. The transient recovery voltage characteristics of the source are not specifically set, and it is believed that its effect is negligible to the out come of the test. Note that the primary source must be capable of providing the power to support the losses in the test transformer and the secondary load circuit without over-load or a change of frequency of more than 2%.

C.1.3.2 Secondary winding loading characteristics

The secondary winding, or windings, should be connected to a continually rated loading system capable of drawing currents of the required magnitude and harmonic content. The loading system can consist of a combination of naturally commutating devices, or active switches, controlling the connection of linear or non-linear devices. The predominant use of reactors and capacitors as loading devices is favorable, as this reduces significantly the power demands on the primary winding source.

For low harmonic content loading tests the use of natural commutating devices, in conjunction with reactor and resistive components has been found suitable. The transformer leakage reactance, stray cable and load resistor leakage reactance have to be accounted for in the circuit design. Appreciable external reactance will significantly reduce the harmonic content of the secondary currents.

For high harmonic content loading tests it is necessary to use active switch devices to enable chopped pulses of current to be drawn from the secondary winding. Multiple loading circuits in parallel can be utilized to share the continuous load and to generate specific additive harmonic components.

Note that since different temperature rise conditions can result from different harmonic loading conditions having the same Harmonic Loss Factor, F_{HL}, the current frequency spectra achieved on test should be documented.

C.1.3.3 Electrical instrumentation requirements

The extended range of frequency of voltages and currents that are present in this test circuit place extra demands upon the calibration and accuracy of the instrumentation system at higher frequencies. The complete system should have a proven acquisition bandwidth of not less than 3 kHz, including the voltage and current transformers and the recording system. The Fourier analysis should be capable of resolving a 3 kHz signal by utilizing data from a sufficiently wide data window to maintain accuracy.

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C.2 Alternate simulated load temperature rise testing procedures[14]

The purpose of the test is to establish the top oil temperature rise in steady-state condition, with dissipation of total loss equal to the loss at the nonsinusoidal load current, and rated sinusoidal transformer voltage. The test should also establish the average winding temperature rise above oil under the same conditions for liquid-filled transformers, and the average winding temperature rise above ambient for dry-type transformers.

C.2.1 Test method

The test method used may be the loading-back method, the impedance kVA method, or the short circuit (separate load loss and excitation test) method in accordance with IEEE Std C57.12.90-1993 or IEEE Std C57.12.91-1995 provided the load is adjusted to compensate for harmonic losses.

C.2.2 Dry-type transformers

The basic premise of the simulated test is to determine the temperature rises after inducing losses equivalent to the losses generated by nonsinusoidal load current. These harmonic losses are simulated by increasing the test current by an appropriate amount according to the following methods.

C.2.2.1 Load loss simulation Method I

As an alternate to the actual loading method described above, a less accurate simulation may be performed. This simulation requires less equipment and should be used with caution, since it is possible to overload one winding significantly. As such, the procedure is most suitable for small units where the winding eddy losses are similar for both the high-voltage and low-voltage windings.

The load losses supplied by the transformer under test ($P_{LL–T}$) are monitored and maintained during the test. These losses are determined as follows:

$$P_{LL–T} = P_{DC} \times (1 + F_{HL} \times P_{EC}) \times T_C \quad \text{W} \tag{C-1}$$

where

P_{EC} (pu) = assumed eddy-current losses under rated conditions in per unit of rated load I^2R loss calculated as follows:

$$\frac{P_{AC} - P_{DC}}{P_{DC} \times T_C^{\,2}}$$ for transformers rated 300 kVA or less, and

$$\frac{C \times (P_{AC} - P_{DC})}{P_{2-DC} \times T_C^{\,2}}$$ for transformers rated more than 300 kVA

C = 0.7 for transformer having a turns ratio greater than 4:1 and having one or more windings with a current rating greater than 1000 A, or

[14]CAUTIONARY NOTE: This document gives simplified calculation methods that can give reasonable estimates for loading. Implicit within this simplified method is the premise that for the same harmonic loss factor, the same losses and hence temperature rise will be produced. This is not necessarily true. Harmonic loading of transformers gives rise to higher losses and their distribution within the transformer is very different from standard 60 Hz losses, and their magnitudes and location are dependent upon complex calculations of geometry and flux penetration depths. These loading methods, therefore, do not give a good simulation of the loss spatial distribution, and hence should not be used as definitive methods for the determination of hot-spot temperatures in windings, core or structural components.

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0.6 for all other transformers;

$P_{2\text{–DC}}$ = the I^2R losses for the inner winding with the winding at ambient temperature; and

$$T_C = \frac{T_s + T_k}{T_a + T_k} \text{ temperature correction factor}$$

where

T_s = the maximum acceptable insulation system temperature rise plus 20 °C;
T_a = the ambient temperature at which the impedance losses and the I^2R losses were determined;
T_k = 234.5 °C for copper windings or 225 °C for aluminum windings.

NOTE—The value of T_k may be as high as 230 °C for alloyed aluminum.

The impedance losses and the I^2R losses should be determined in accordance with IEEE Std C57.12.90-1993 or IEEE Std C57.12.91-1995.

C.2.2.2 Load loss simulation Method II

This method is similar to Method I above, except it attempts to account for the different eddy-current losses for each winding by establishing an equivalent harmonic current. It may therefore be more appropriate for larger transformers and for units having large differences in the high-voltage and low-voltage winding eddy losses. This simulation also requires less equipment than the actual loading method, but requires a number of mathematical corrections.

The load current supplied by the transformer under test may be determined from Equation (17). The maximum designed current rating is defined as

$$I_{max}(\text{pu}) = \sqrt{\frac{P_{LL-R}(\text{pu})}{1 + F_{HL} \times P_{EC-R}(\text{pu})}} \quad \text{pu}$$

The per-unit test current required to simulate the losses for the harmonic loading in each winding, referred to the rated current, is given by

$$I_T(\text{pu}) = \sqrt{\frac{1 + F_{HL} \times P_{EC-R}(\text{pu})}{P_{LL-R}(\text{pu})}} \quad \text{pu} \tag{C-2}$$

Since the per-unit eddy-current losses in each winding are normally not the same, the following factors are defined for convenience:

$$\alpha_1 = \sqrt{\frac{1 + F_{HL} \times P_{EC-1-R}(\text{pu})}{P_{LL-1-R}(\text{pu})}} = \sqrt{1 + F_{HL} \times P_{EC-1-R}(\text{pu})} \tag{C-3}$$

and

$$\alpha_2 = \sqrt{\frac{1 + F_{HL} \times P_{EC-2-R}(\text{pu})}{P_{LL-2-R}(\text{pu})}} = \sqrt{1 + F_{HL} \times P_{EC-2-R}(\text{pu})} \tag{C-4}$$

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The current for each winding may then be calculated as follows:

$$I_{1-T} = \alpha_1 \times I_{1-R} \quad \text{amperes} \tag{C-5}$$

and

$$I_{2-T} = \alpha_2 \times I_{2-R} \quad \text{amperes} \tag{C-6}$$

Since the current of only one winding may determine the value of the test current, an intermediate value is established as a compromise.

$$I_T\,(\text{pu}) = \alpha \times I_R\,(\text{pu}) \quad \text{pu} \tag{C-7}$$

where

$$\alpha = \frac{\alpha_1 + \alpha_2}{2} \tag{C-8}$$

The individual temperature rise values determined from testing with this compromise load current are then corrected by the following equations:

$$\theta_1 = \theta_{1-T} \times \left(\frac{\alpha_1}{\alpha}\right)^2 \tag{C-9}$$

$$\theta_2 = \theta_{2-T} \times \left(\frac{\alpha_2}{\alpha}\right)^2 \tag{C-10}$$

Note that this procedure overloads one winding during the temperature test. If the winding to be overloaded is not capable of withstanding the expected temperature, a lower value of α may be used. This value should not be less than the lower value of α_1 and α_2.

C.2.3 Liquid-filled transformers

The top-oil rise must first be determined for liquid-filled transformers, before the winding temperature rises may be established. This requires the injection of the total losses, which is composed of the load loss plus the no load loss. The load loss is the total loss developed from the non-sinusoidal load current and includes the winding dc losses, winding eddy losses and the other stray losses. The relationship of these losses is defined by Equation (19):

$$P_{LL} = P + F_{HL} \times P_{EC-R} + F_{HL-STR} \times P_{OSL-R} \quad \text{W}$$

The no-load loss corresponds to the rated transformer voltage. The total injected losses are then measured and the fundamental power-frequency current is adjusted to give the specified test value of the total loss.

When the top-oil temperature rise has been established, the test continues with a sinusoidal test current equivalent to the total load loss (P_{LL}). This condition is maintained for 1 h during which measurements of oil and cooling medium temperatures are made. The equivalent test current is determined by Load Loss Simulation Method II, in section C.2.2.2 above. At the end of the temperature rise test, the temperatures of the two windings are determined according to standard methods in the references noted in section C.2.1.

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Annex D

(informative)

Tutorial discussion of transformer losses and the effect of harmonic currents on these losses

Power transformers with ratings up to 50 MVA are almost always of core form construction. High-voltage and low-voltage windings are concentric cylinders surrounding a vertical core leg of rectangular or circular cross section. The vertical core legs and the horizontal core yoke members that constitute the magnetic circuit are made up of thin steel laminations. In the top and bottom yoke regions there are usually external clamping structures (clamps) that may be made of either metallic or insulating materials. Oil-immersed transformers are contained within a steel tank, while dry-type transformers may be either freestanding or surrounded by a metal enclosure. If direct current is passed through the transformer winding conductors, a simple I^2R loss will be produced, where R is the dc resistance of the winding. However, if an alternating current (ac) of the same magnitude is passed through the winding conductors, an additional loss is produced. This can be explained as follows. When the transformer windings carry the ac current, each conductor is surrounded by an alternating electromagnetic field whose strength is directly proportional to the magnitude of the current. A picture of the composite field produced by rated load current flowing through all the winding conductors is shown in Figure D.1, which is a cross-sectional view through the core, windings, clamps, and tank. Each metallic conductor linked by the electromagnetic flux experiences an internal induced voltage that causes eddy currents to flow in that conductor. The eddy currents produce losses that are dissipated in the form of heat, producing an additional temperature rise in the conductor over its surroundings. This type of extra loss beyond the I^2R loss is frequently referred to as "stray loss." Although all of the extra loss is an eddy-current loss, the portion in the windings is usually called "eddy-current loss" (P_{EC}), and the portion outside the windings is called "other stray loss" (P_{OSL}).

Eddy-current loss in winding conductors is proportional to the square of the electromagnetic field strength (or the square of the load current that produces the field) and to the square of the ac frequency. Other stray losses are generally proportional to current raised to a power slightly less than 1, because the depth of penetration of the electromagnetic flux into the other metallic parts (usually steel) varies with the field strength. (For very high-frequency harmonic currents the electromagnetic flux may not totally penetrate the winding conductors either, but it is conservative to assume that the eddy-current loss, P_{EC}, is proportional to the square of the harmonic current frequency.) When a transformer is subjected to a load current having significant harmonic content, the extra eddy-current loss in winding conductors and in other metallic parts will elevate the temperature of those parts above their normal operating temperature under rated conditions. Experience has shown that the winding conductors are the more critical parts for determination of acceptable operating temperature, so the objective should be to prevent the losses in winding conductors under harmonic load conditions from exceeding the losses under rated frequency operating conditions.

The inner winding of a core form transformer typically has higher eddy-current loss than the outer winding, because the electromagnetic flux has a greater tendency to fringe inwardly toward the low reluctance path of the core leg. Furthermore, the highest local eddy-current loss usually occurs in the end conductors of the inside winding. This is a result of the fact that this is the region of highest radial electromagnetic flux density (closest spacing of the radially directed flux lines in Figure D.1) and the radial flux passes through the width dimension of the rectangular winding conductor. Since the width dimension of a conductor is typically 3–5 times the thickness dimension and eddy-current loss is proportional to the square of the dimension, high loss is produced in the end conductors. Certain simplifying assumptions have been made in this recommended practice about the relative proportions of the eddy-current losses in the inner and outer windings and the relation between average eddy-current losses and maximum local eddy-current losses. These assumptions, which are conservative, may be used when specific knowledge of the eddy-current loss magnitude is not

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available. However, more accurate calculations can be made if design values of eddy-current losses are available from the transformer manufacturer.

The recommendations for determination of acceptable operating conditions contained in this recommended practice are based on the calculation of a "transformer capability equivalent," which establishes a current derating factor for load currents having a given harmonic composition. Equation (17) provides a calculation of the maximum rms value of a nonsinusoidal load current (in per unit of rated load current) that will ensure that the losses in the highest loss density region of the windings do not exceed the design value of losses under rated frequency operating conditions. Example cases are presented for the situations where design eddy-current loss data are available from the manufacturer or where they are not.

Harmonic currents flowing through transformer leakage impedance and through system impedance may also produce some small harmonic distortion in the voltage waveform at the transformer terminals. Such voltage harmonics also cause extra harmonic losses in the transformer core. However, operating experience has not indicated that core temperature rise will ever be the limiting parameter for determination of safe magnitudes of nonsinusoidal load currents.

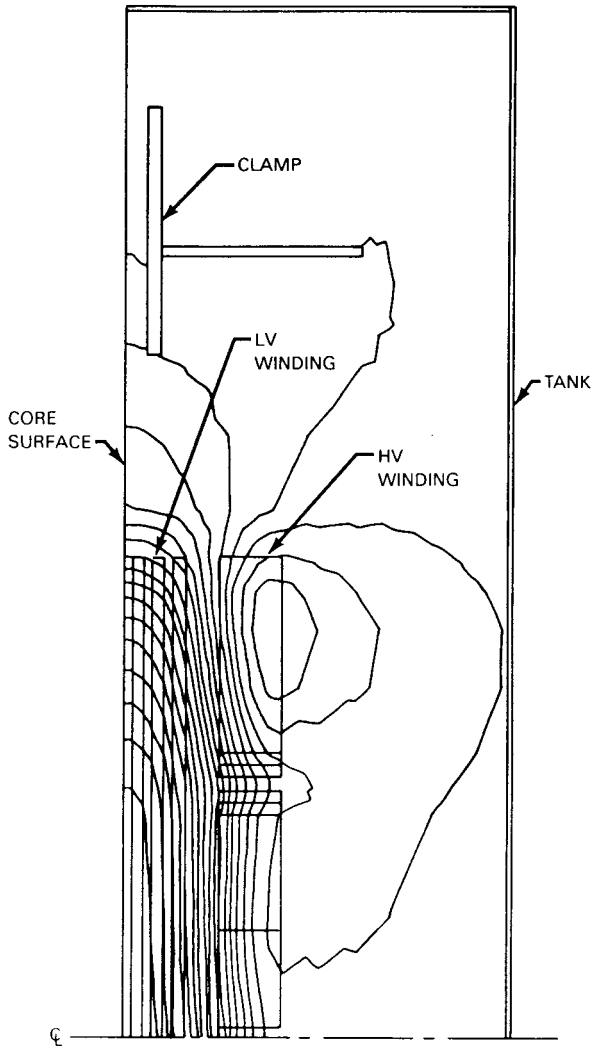

Figure D.1—Electromagnetic field produced by load current in a transformer

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